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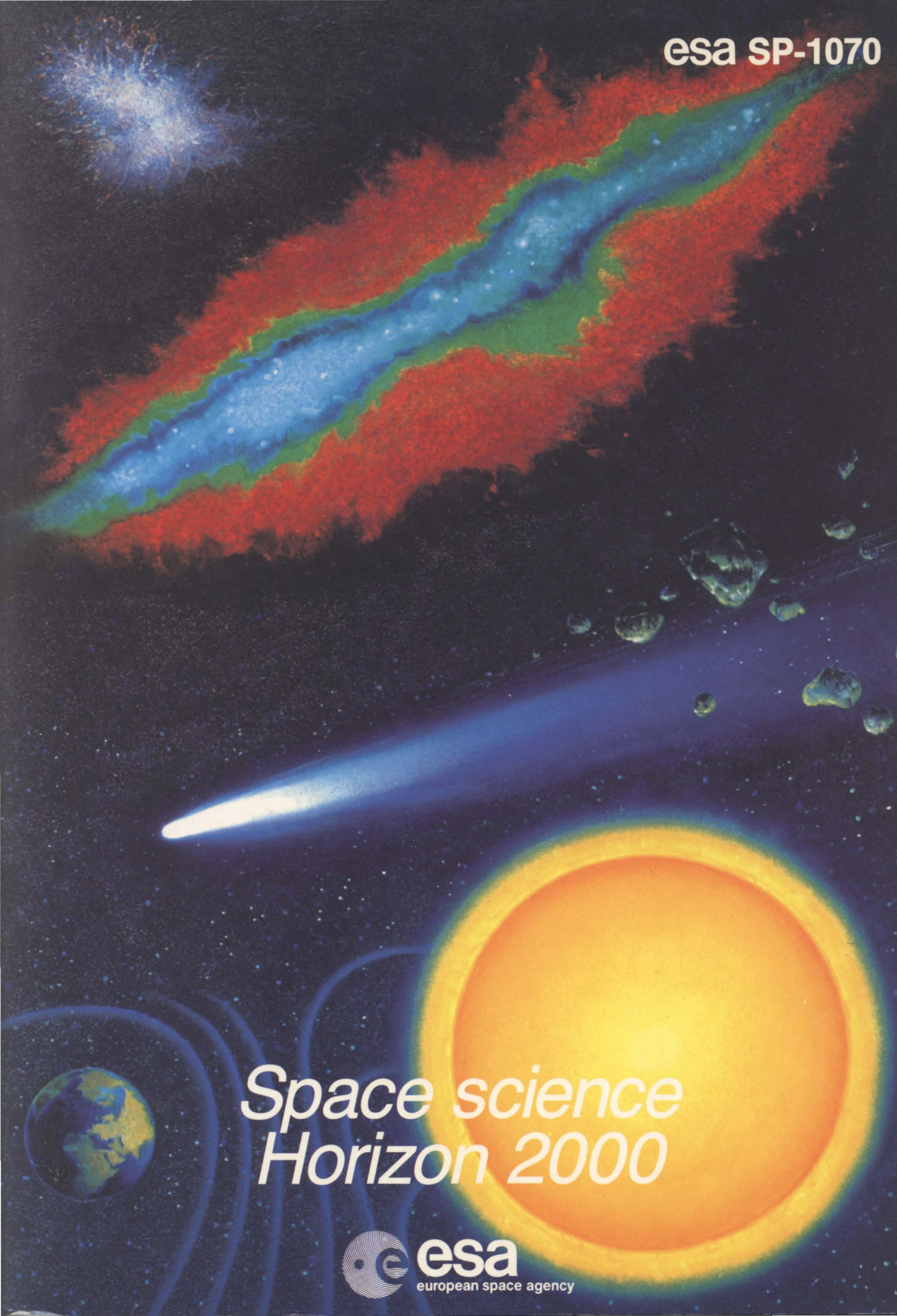

Space science
Horizon 2000

esa
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December 1984

European Space Science

Horizon 2000

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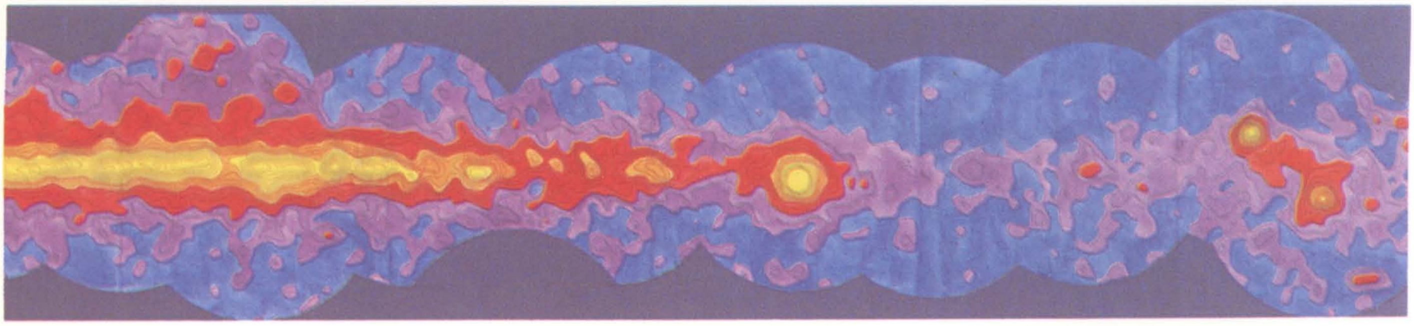
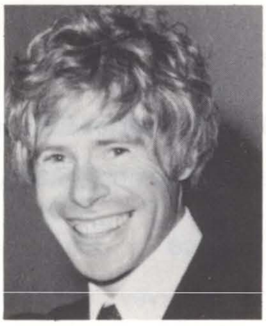


Foreword



This book is an expanded version of the long-term planning report 'Space Science: Horizon 2000' as issued by the Survey Committee in July 1984.

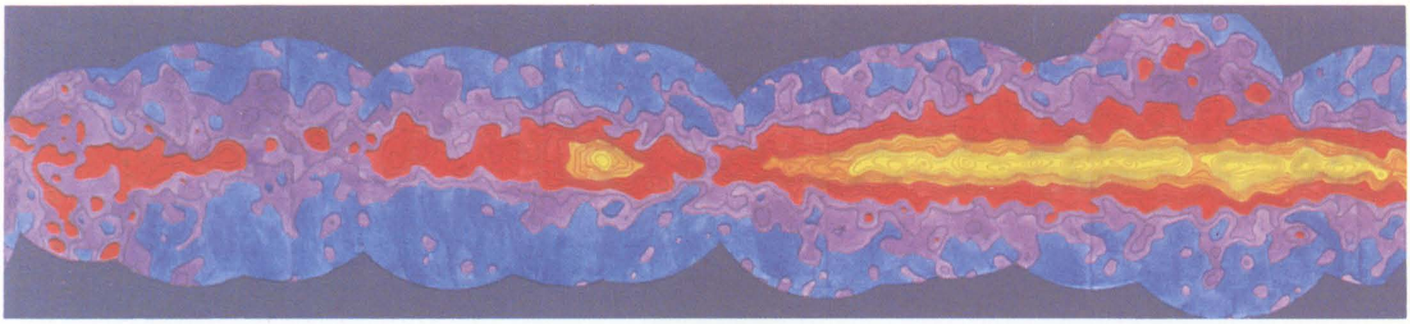
It contains the detailed reports of the topical teams in the area of solar system science and the contributions of the members of the Astronomy survey panel and support team.

The book starts with the programmatic considerations and relations with other branches of fundamental science as contained in the Survey Committee report (cf. Chapters 1, 2, 3, 4, 7 and 8). To introduce the in-depth evaluation of the various disciplines in space science, Chapters 5 and 6 of the Survey Committee report have been reproduced. The final chapters address the mission concepts received and considerations on industrial benefits.

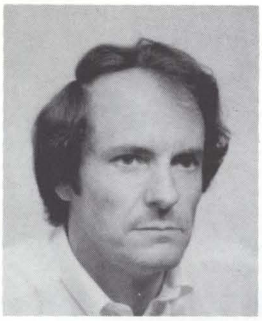
In the individual reports reference is made to on-going studies on specific missions. It should be noted that apart from the mission concepts, the Survey Committee also took into account on-going study activities related to XMM, First, Columbus-UV, Quasat, Soho, Cluster, Agora and Cassini. This procedure has led to some duplication and/or overlap between the chapters taken from the Survey Committee report and the individual contributions. To avoid misunderstanding or misinterpretation of the various contributions, it was decided not to undertake closer harmonisation.

Roger-Maurice Bonnet
Director of the Scientific Programme

Paris, December 1984



Introduction



This report presents the outline of a long term plan for the disciplines of space science falling within the terms of reference of the ESA Directorate of Science. The study, which led to the long term plan proposed in this document, was initiated by the Director of the Scientific Programme in September 1983 and was coordinated by a Survey Committee composed of scientists from different areas of fundamental science.

The main thrust for this long term plan is to be found in the fact that space science has progressed over the past twenty five years from the pioneering and exploratory stage to a firmly established mature branch of fundamental science. In addition, the desirability and potential for space science missions of a number of planned technological developments, such as new launchers and in-orbit infrastructure (in particular the Space Station) were to be globally assessed.

Space science in Europe has in the past contributed very significantly to the advancement of science; however, now is the time to identify what the main thrusts in European space science should be for the coming decades to consolidate Europe's position in the forefront of scientific development. In order to make this effort useful, the long term plan should strike a balance between being specific, on the one hand, and, on the other, incorporate sufficient flexibility to cope with the rapid evolution intrinsic in every field of scientific research.

The main thrusts in a twenty-year programme need to be identified now in order to accommodate appropriate technological developments and to indicate to the scientific community at large what Europe has to offer in terms of scientific projects and/or missions in space. The European community has itself been directly involved in providing the elements for the identification of these main thrusts and this has been very successful indeed: a massive response to a call for mission concepts from the Director of the Scientific Programme indicated that there is a large and eager interest in the ESA science programme. The fact that the Survey Committee reached a consensus in what the main thrusts of the future should be also demonstrated the conviction of many European scientists that the route to follow is to establish a priori a consistent and coherent plan where certain basic choices are made, in order to fit into a realistic budgetary envelope.

I wish to express here my appreciation for the persistent efforts and dedication of the many scientists who directly participated in this exercise to reach a challenging, albeit unavoidably restricted, plan for European space science in the coming decades. These efforts and the overwhelming response of the science community are the best proof of the vitality of Europe in the field of space science; it deserves a future which does proper credit to what has been built up today.

Johan Bleeker
Chairman of the Survey Committee

Part I – A long term programme for European space science

A beginning, ESRO-2/Iris was the first ESRO satellite to be successfully launched. It was placed in orbit from the Western Test Range, California on 17 May 1968. After nearly three years, and 16282 orbits in total in which it studied cosmic rays and solar particles, it re-entered the atmosphere on 8 May 1971.

1. Actions, Proposals, Conclusions – Survey Committee Report

Over the past 25 years, space science has progressed from the pioneering and exploratory stage to a firmly established mature branch of fundamental science.

The time has come to identify what the main thrusts of European space science should be for the coming decades to consolidate Europe's position in the forefront of scientific development.

The opportunity to involve directly and thoroughly the European scientific community was firmly grasped. The reward was an enthusiastic response, a deep analysis of what could and should be tackled, and a realistic assessment of the constraints which had to be faced.

The main thrusts in a twenty-year programme have been identified, so that the long term technological developments which are essential to the programme may be advanced, and as an indication to the scientific community at large what Europe has to offer in terms of space science projects and missions.

1.1 Introduction and summary conclusions

This book contains the results of a study on the outlook for space science in the areas

- Astronomy,
- Solar and Heliospheric Physics,
- Space Plasma Physics,
- Planetary Research,

which are within the responsibility of the ESA Directorate of Science, and on the role of Europe in this domain of research. It proposes a long term model programme for ESA until the turn of the century and assesses the corresponding realistic financial requirements.

The study was carried out between October 1983 and July 1984 directly involving the European scientific community. A call for Mission Concepts was addressed by the Director of the Scientific Programme to the community in November 1983. The strong degree of interest was obvious from the 77 replies received. Furthermore, a Survey Committee and a number of Topical Teams and Panels were set up involving about 50 European scientists. The Survey Committee co-ordinated the entire effort. It was composed of the Space Science Advisory Committee members and invited scientists from other international scientific research organisations, CERN, ESO, ESF and IAU. The Topical Teams/Panels analysed the scientific priorities and requirements of the different research topics and identified the means by which Europe could achieve them taking into account the Mission Concepts received and other inputs. A list of the members of the Survey Committee, Topical Teams and Survey Panels is given on page 00.

The Survey Committee, together with the Topical Team and Panel Chairmen, discussed their findings, and, finally, in a three-day meeting in Venice, built up, from the analysis and priorities prepared by the teams a coherent overall programme for European space science in the next 15 to 20 years.

This programme, founded on four major elements in solar/heliospheric/plasma physics, planetary research, and astronomy, which have been recognised as its four 'cornerstones', achieves, through a relatively moderate increase in funding requirements, a quantum jump in scientific significance and offers the capability of frontline research to the European community. It gives Europe the means of being an equal partner in a worldwide prospectus in space science, while honouring its cultural heritage and scientific tradition.

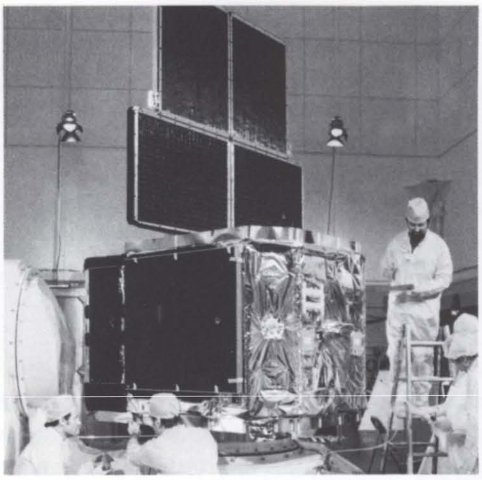
1.2 Motivations and Guidelines

Space science has progressed in the past 25 years from its initial exploratory stage, to establish itself as a basic component of fundamental research.

The ESA space science programme has contributed in a financially modest but scientifically significant way to this evolution.

Because of the initial uncertainties and exploratory nature of space research, no general framework was established and missions were selected on an ad hoc basis, through a competitive procedure, as and when funds became available.

Space Science activities in Europe have been highlighted by their very successes. That, together with the degree of maturity and sophistication now reached, makes it necessary for Europe to put into perspective its future space science programme.



Exosat — X-ray observatory

Launched:	26 May 1983
Decay/Expiry:	2 years
Design life:	2 years

Scientific considerations

Space science has brought about major advances in fundamental research; advancement of science is therefore the basic goal of space science missions quite independently of considerations of a technological, industrial and political nature. Space science missions must, in quality and quantity, match the general evolution of science today.

Looking first at the *quality* of present and future missions, one can see a general trend towards more complex and demanding missions throughout the world. This is particularly evident in astronomy, astrophysics, and in planetary research, although complex multi-spacecraft missions are also being requested by the space plasma, and solar-terrestrial physicists. This trend should not come as a surprise. It is the logical evolution following a phase of exploration in the 60s and 70s, that European scientists, acting in a highly competitive international field, want to have access to these large facilities which offer the most sophisticated possibilities of data capture, retrieval, and analysis. They naturally wish to carry out frontline science in conditions at least equal to their colleagues in other parts of the world. Hence, in most areas of space research, complex facilities have to be considered: a testimony to the maturity reached in this field of research.

In addition, there should still remain room for simple but ingenious missions both to cover as yet unexplored areas and to keep pace with the shifting needs of science. A programme composed solely of large missions would be in danger of losing its scientific vigour.

The parameter of *quantity* is directly related to the size of the community and to the need to secure continuity of research. The size of the community is known: in excess of 2000 scientists in Europe are at present making use of the results of space investigations. A scientific group must be given reasonably frequent flight opportunities so that it may develop its line of research. Analysis shows that flight opportunities every three to five years, allowing between two and three experiments in a decade, are necessary if a scientific group is to remain viable. Failure to achieve this level will lead to scientists prefering to work on other topics; and Europe will then forfeit an essential element of basic research. Other parts of the world are not prepared to take that risk.

It is instructive to compare the likely support within NASA for the same disciplines. After a period of stagnation during recent years (656 M$ in 1983; 783 M$ in 1984), the equivalent budget of NASA has climbed to 964 M$ in 1985. Although a straight comparison is not possible due to the different budget structures in ESA and NASA, there is a ratio of 1 to 7 between the two Agencies which is very significant indeed and difficult to explain. It should be noted that in other domains, such as high energy particle physics and radio astronomy, the European and US budgets are essentially comparable. The scientific advisory bodies of the Agency and of the ESF have strongly and repeatedly emphasised their concern on this subject.

A long term programme, reflecting the above considerations, will constitute a reference both worldwide and within Europe for space research activities and will help scientific groups to determine their internal research programmes.

Technological and industrial consideration
Scientific projects constitute 'a technological pull' in the words of industry itself (Proceedings ESA/EUROSPACE meeting, Nice, January 1984). Advanced optics, cryogenic systems, high accuracy control systems, high precision mechanisms and many other instruments and systems were developed for scientific programmes.

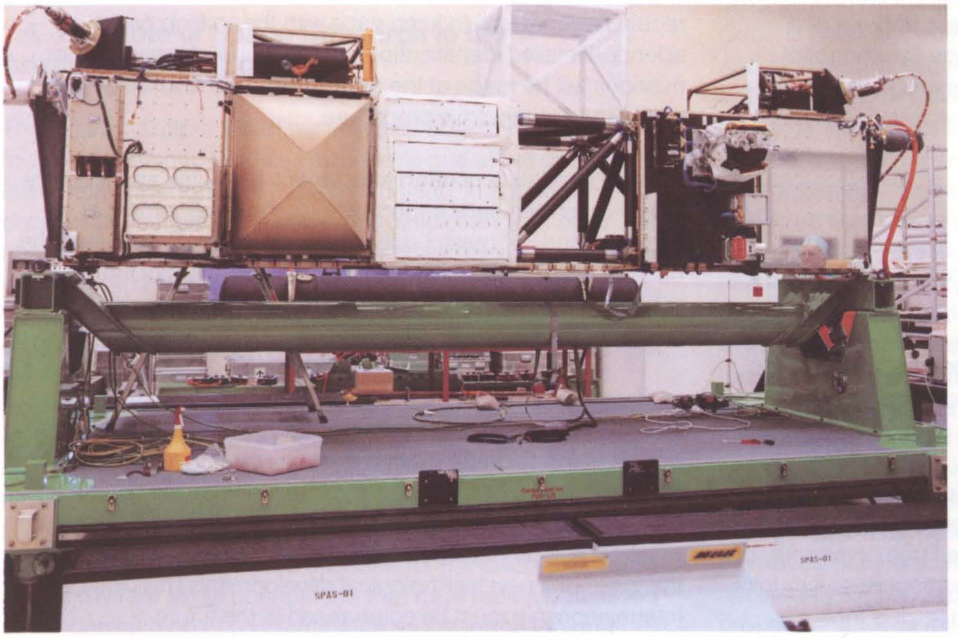
Indeed, it is in the nature of scientific quest that successive projects always strive for the as yet unattainable and push technologies to their ultimate performance. However, technological prowess is the result of a well-planned and homogeneous effort by industry, the scientific institutes and ESA. Room for imagination is vast, but improvisation under the constraints of time can be financially disastrous and may lead to acceptance of significantly lower performances than expected. Careful advanced planning of the technological development likely to be required in particular by the complex facilities, is thus essential for the conduct of a programme of technologically advanced projects, under conditions of minimum risk.

For the reasons above, scientific projects are intensive users of highly skilled teams in industry. Here again, the basic need for continuity is found as in the scientific institutes. Taking into account typical project development times, some eight to 10 science projects in a decade would provide European industry with this continuity, failing which these highly skilled teams will quickly move to more rewarding activities.

Advanced planning and a coherent programme are a necessary measure to build confidence in industry and to allow it proper preparation, advance recruitment and availability of the essential skills.

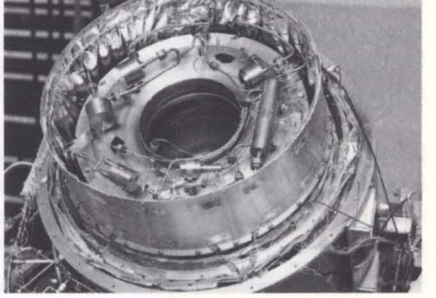
Policy considerations
There are two elements to be considered when deciding on a policy: the European viewpoint, and relations with other Agencies outside Europe.

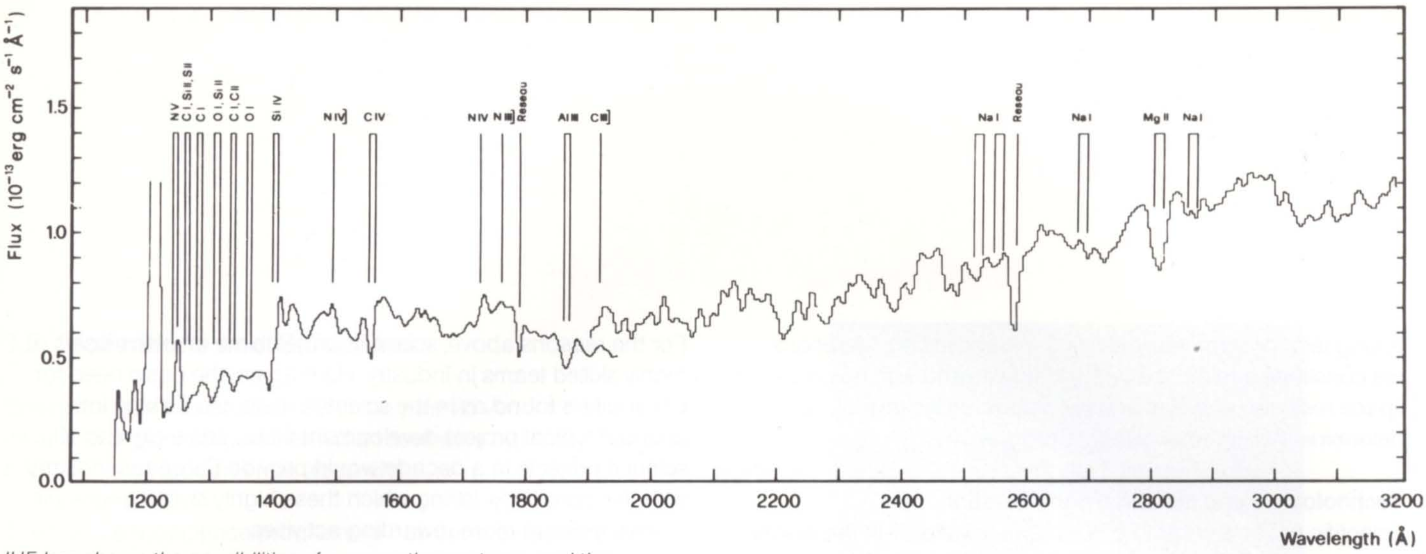
At the *European* level, the challenges to be faced at present are not different from those that led to the foundation of ESRO. Only by pooling its resources can Europe expect to have an independent programme capable of matching the larger programmes of NASA and others. At present, national programmes exist in Europe which contribute significantly to the space effort. However, a simple comparison of resources makes it obvious that single national programmes can only be



SPAS-01 during check-out at Kennedy Space Centre, showing the heat pipe flight verification experiment just left of centre.

Superfluid helium cryogenic dewar – CRHESUS





IUE has shown the possibilities of cooperative ventures, and the flexibility of operation needed to obtain the best results. The spectrum of supernova Johnson as observed by IUE as a 'target of opportunity' in April 1979. The most prominent absorption and emission features are identified.

competitive on a worldwide scale in limited areas and must eventually find their place within an overall European endeavour with the ultimate goal of optimising the European space research effort. Coordination between ESA's and national programmes cannot, however, take place unless a long term strategy is defined. This should lead to the establishment of a reference frame for European space research as a whole within which the ESA programme and the national programmes progress in a coordinated fashion.

From the viewpoint of relations with *other Agencies* and in particular *NASA*, it would be in the best interests of European scientists that the European programme be coordinated with those of other Agencies outside Europe. This will open additional possibilities to European scientists, will avoid wasteful duplication, and increase the scientific return with respect to the total investment made. This presupposes the existence of a long term European programme, against which relations with other Agencies' programmes can be evaluated a priori, thereby avoiding the intrinsic weakness and risk of a posteriori reactions to events initiated outside the control of Europe. This is all the more important at present in view of the vigorous major development by NASA of the space station.

1.3 Criteria and Framework

An independent European long term programme should obey the following main criteria:

i. scientific standard
This is the paramount criterion. Cultural heritage and scientific tradition demand that Europe's scientific goals be set at the highest standard.

ii. have a suitable mix of large and smaller projects
Large projects tend to be complex and expensive; their scope should be scientifically versatile and serve a large community of users. A facility requires preparation by the scientific community and prior scientific and technical development. It is thus necessary that smaller projects be included in the overall programme with more specialised scientific aims and/or as a stepping stone towards the larger facility. National programmes could play an important role in this latter category and in the related technologies.

iii. have flexibility and versatility to match the scientific evolution
Plans for missions and designs of instruments tend to be frozen many years in advance, in particular in the case of large complex missions. These require long preparation at the scientific, technological and policy level. In setting up the long term programme, it will thus be essential that, where possible, the large and complex facilities should be readily identified, and the consequent rigidity introduced in the programme be accepted. Having established the major missions as the 'cornerstones' of the programme, provisions are to be made within the overall long term programme for a number of typical but as yet unidentified medium and small size missions to regain flexibility and to keep pace with the shifting needs of science. Detailed identification and selection of these smaller missions will be made at the appropriate time and follow the established competitive procedure.

iv. give continuity of effort to scientific institutes and industry
This is of fundamental importance for the development of a coherent and successful scientific programme. Considering the number of scientific institutes and the distribution of industries in Europe, a total of some 12 to 15 missions in the next 15 years is required.

v. have a high technological content
The basic objective of a science programme is, of course, the benefit to the scientific disciplines themselves. It must, however, be recognised that a strong interrelationship exists between scientific development and technological advance. Scientific projects 'pull' technology, and vice versa: science blossoms in the wake of a new technological development. This close interrelationship must be emphasised in the future.

vi. remain within realistic budgetary limits
It is quite unrealistic to propose that Europe should devote as much as NASA to space research, albeit that the US and Europe have similar GNPs, population and space communities. On the other hand, the present ESA mandatory science budget, still constrained within the boundaries established in 1971, is completely inadequate to meet the objectives stated above. At present ESA can only develop one medium/small size project every two years, with no prospect whatsoever of engaging in the larger projects now requested in most disciplines, other than as subordinate partners in NASA conceived and developed missions. Such a degree of dependence on other Agencies' programmes is not compatible either with the ambitions and role of Europe, or with its cultural heritage.

An increase of the present level of funding is thus necessary to achieve an autonomous programme of a high standard. Careful analysis should, however, be made in order to formulate a programme requiring realistic and feasible increases over the present European effort.

vii. maintain a proper balance between purely European and cooperative projects with other Agencies
The European programme should be autonomous but not isolated. It should be well matched to worldwide plans to avoid wasteful duplication. A certain degree of interdependence by way of cooperative projects would be beneficial both because of the intrinsic scientific advantage and as a means to maintain the project costs within the limits of European capabilities.

1.4 The Role of Space Research in the Advancement of Science

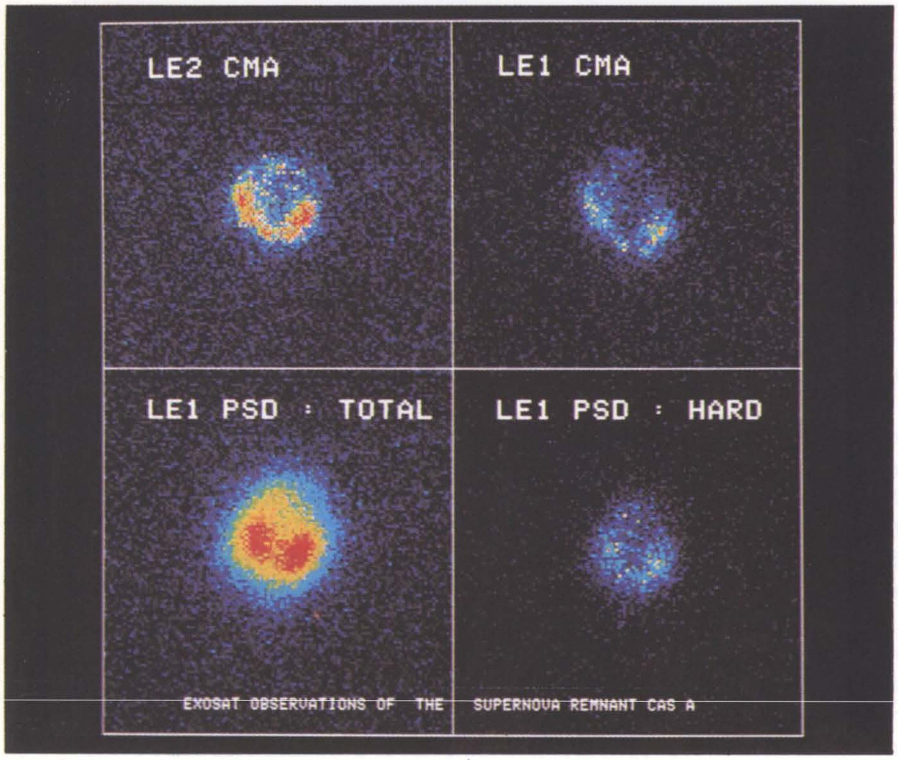
The detailed exploration of the Universe from our solar system to the most remote distances represents one of the greatest intellectual adventures of modern mankind. The past two decades or so have witnessed a dramatic change in our views about the Universe and its constituents, an ongoing revolution whose implications are still to be fully understood not only in the scientific context but also from the philosophical standpoint. It is probably correct to say that such a widening of the horizon in such a short time represents something unprecedented in human history with the exception perhaps, and in a relative sense, of the time of Galileo. The great thrust made by Galileo resulted from the use of a new optical device, the telescope, a big step forward in the technology of his time. In a similar way the advances in technology characteristic of modern times have provided the basis for the discovery of a completely new set of phenomena that have radically modified our understanding of problems such as the formation and evolution of galaxies, the formation of stars and of the solar system and evolution of the Universe.

In this advancement of our knowledge, space science has played a key role not only through the direct exploration of the solar system, but because the installation of instruments on-board orbiting satellites has permitted the systematic investigation of the Universe in those parts of the electromagnetic spectrum (such as the infrared, the ultraviolet, the X- and γ-rays) which are blocked by the Earth's atmosphere. This opening of new observational windows has revealed an extremely rich panorama and has provided data essential to the understanding of basic astronomical and astrophysical phenomena. An unsuspected picture of the Universe has emerged dominated by cataclysmic events, explosions and shocks, with releases of immense amounts of energy. The old serene Universe of Aristotle, populated by perfect objects moving in silent harmony, and which had survived for centuries has been shattered conclusively by space observations.

Space science is thus today an essential element in the development of science. Its impact extends well beyond the frontiers of astronomy and of the solar system into the domains of fundamental physics, plasma physics, atomic physics and Earth sciences.

1.5 Relationship with other disciplines

i. Elementary particles and fundamental physics
Present observational evidence indicates that the Universe can be described by the simplest homogeneous isotropic models of General Relativity, whereby it has expanded from a very hot and high density state some 20 thousand million years ago (the hot big-bang). Of particular interest for particle and fundamental physics are the initial moments when the temperature of the Universe was so high that the corresponding thermal energy of the particles would have exceeded the threshold above which all four fundamental forces of nature are expected to be unified. As cooling occurs, due to expansion, the gravitational force will uncouple from the other forces until another threshold energy is reached below which the strong interaction will also eventually uncouple from the weak and electromagnetic interactions. The values of these threshold energies are far above the present and future possibilities attainable with particle accelerators. Therefore the Universe provides the natural laboratory in which it is hoped that the unified theories of physics can be tested. Conversely, the application of these theories to the early Universe has led to theoretical schemes which seem to provide a natural (but not necessarily simple) explanation of basic cosmological properties, such as the excess of matter over antimatter, the



Images of the supernova remnant Cassiopeia-A as recorded by the low-energy telescope proportional counter cameras on Exosat

entropy of the Universe and its high degree of isotropy. Moreover, most of the mass of the Universe, and in particular the hidden mass inferred from the dynamics of galaxies and of clusters of galaxies, could be in the form of massive neutrinos or other massive particles such as photinos and axions predicted by supersymmetry theories. Constraints on the properties of these particles can be set by the observations of the large scale distribution of matter and of the spectral shape distortions of the universal black-body radiation field. However, if the lifetime of these particles is long enough, then the photons produced by their decay might be directly observed. Thus, for instance, photinos and massive neutrinos in the halo of our Galaxy or in nearby galaxies could decay giving rise to measurable fluxes of very soft X-rays or γ-rays respectively. Also neutrino fluxes from the solar interior are currently posing questions in relation to our solar models, whose answers may throw light on the questions of neutrino mass and lifetimes.

Of course, the detection of such features, which could be directly related to the existence of certain types of elementary particles would have an enormous impact both on particle physics and on cosmology. The hot big-bang model already provides rather powerful constraints for elementary particles. For instance, detailed computations of the synthesis of primordial elements show that the number of different types of neutrinos cannot exceed four, otherwise the gravitational pull associated with them would be too large and too much primordial helium would be produced. This in turn sets constraints on some versions of grand unified theories. Although the available evidence from solar and astronomical observations can be better understood in terms of the hot big-bang, the application of this model to the real Universe still raises many questions, and the important consequences outlined above call for a powerful observational programme capable of checking with certainty its validity.

Another important area of research closely related to particle physics is the study of the cosmic radiation. Here, the analysis of the composition of the cosmic rays may provide information on elementary processes taking place at the sources. The detection of a flux of antiprotons above a few hundred MeV, which is apparently difficult to account for by the collision of ordinary matter, may provide an example. Another example is given by observation of strongly increased ratios of isotopes in elements like Neon which may be due to advanced nucleosynthesis associated with cosmic ray sources.

ii. Condensed matter, black holes and General Relativity

The gravitational attraction under cosmic conditions can lead to the formation of highly collapsed objects such as neutron stars and black holes. This gives, in principle, the possibility of studying the physics of highly condensed matter under extreme conditions normally not attainable in the laboratory. At the same time an opportunity is offered to identify situations where the gravitational fields are so strong that gravitational theories, such as Einstein's General Relativity can be tested.

Neutron stars provide a site where matter has been packed by gravitation to nuclear densities and where extremely strong magnetic fields are generated as a result of the gravitational compression of the progenitor star. Magnetic rotating neutron stars are easily spotted via the detection of pulsed radio and/or X-ray emissions. The systematic studies of the timing of the pulses provide information on the dynamics of these objects, and indirectly on their internal structure. Also X-ray observations provide the most direct tool to study the properties of accretion flows of matter onto the surface of neutron stars and to probe their thermal properties. Thus, an unprecendented handle in the investigation of the properties of ultra-dense matter in the presence of extremely strong magnetic fields is obtained and it is therefore hoped that theoretical predictions based on extrapolations from laboratory physics can be tested.

The formation of rapidly spinning neutron stars may lead to a copious production of gravitational waves. Gravitational wave detectors were built in the hope of detecting these bursts of gravitational radiation, but the results have so far been negative. However, astronomers have discovered a celestial object whose dynamics now appear to be controlled by the release of gravitational waves: this is a binary system composed of two pulsars, that is to say, two neutron stars orbiting around each other. This is a further confirmation that the Universe in a way provides the most natural laboratory for testing gravitational theories.

In future, solar orbiting satellites passing close to the sun, should provide vital data to determine between the competing theories of gravity. It has furthermore been suggested that an advance in the techniques of helioseismology could offer the possibility of using the sun as a detector of gravitation radiation.

Moreover, X-ray observations have permitted the discovery of black hole candidates in binary systems where one of the stars is a collapsed star with a mass exceeding the limit above which no known forces can prevent the gravitational collapse.

An important theoretical prediction is that black holes must radiate energy if quantum effects are taken into account: the production of virtual pairs of particles in the proximity of a black hole may lead to the capture of one of the particles by the black hole while the other is set free. To an outside observer the black hole appears to radiate, and energy conservation requires that it evaporates. Black holes now in their final stages of evaporation could produce bursts of γ-rays which may be searched for by detectors on-board space vehicles.

iii. Plasma and Atomic Physics

The Universe represents an inexhaustible source of plasma and atomic physics phenomena. Almost any astrophysical situation exhibits a wide range of binary and collective interaction conditions relating to atomic collision and plasma physics. One goes from the very hot and dense plasmas embedded in extremely strong magnetic fields close to collapsed objects, to the stars and to the more tenuous and diffuse plasmas to be found in the heliosphere, in interstellar regions and in intergalactic space. Cosmic plasmas are in general characterised by the presence of strong magnetic fields. The origin of these fields in different types of astrophysical conditions is still an unresolved problem.

Another phenomenon is the existence of the so-called 'Galactic cosmic rays', a high energy component of the interstellar medium whose individual particles have mean energies in the GeV range and whose energy density equals that of the thermal gas. Only collective plasma processes can be responsible for this apparently ubiquitous component. Efficient acceleration occurs in such extremely different objects and environments as supernova remnants, pulsars, radio galaxies and quasars.

The only way to go about interpreting the great variety of observed phenomena is by building theoretical models., then comparing predictions with the observations. However, the complexity of plasma physics and the many parameters involved in actual physical systems are such that a sound experimental verification of the theories which are applied is required.

Unfortunately laboratory plasma physics is hampered by the limited size of the apparatus and by the spurious effects introduced by the confinement. The advent of the space age has given access to a very rich laboratory represented by the Earth's magnetosphere, the interplanetary medium, the magnetospheres of the planets and the many new aspects of solar physics. The sun offers a unique laboratory because of its proximity and unobscured electromagnetic spectrum. Studies of high ionised atomic physics, spectroscopy, plasma/magnetic field interaction, magnetic energy and its explosive release in reconnection and annihilation processes have already led to many advancements in our knowledge. In particular such processes also seem to play a fundamental role in particle acceleration. More generally, space plasma physics research has demonstrated that the cosmic plasma observed in the solar system has a cellular structure with very thin boundary layers separating plasma regions of widely different characteristics (different pressure, temperature, composition of the plasma and different electric and magnetic fields). The magnetopause is just one example of such a boundary. These boundaries, or cell walls, are almost impossible to observe by remote methods and can only be identified by means of instruments measuring in situ. It is most likely that this cellular structure is a general property of the Universe and not only of the solar system. It is clear that astrophysics, space science and laboratory physics are intimately interrelated fields essential to the progress of our understanding of basic plasma physics.

iv. Earth Sciences

Space techniques provide a powerful way of studying the Earth as a planet. This obvious fact was realised only recently, but it is now well recognised and a coordinated programme, i.e. the International Geosphere Biosphere Programme, is being proposed to the worldwide community. Although in most cases space techniques only allow measurements of surface phenomena by remote sensing, they do provide quantitative boundary conditions essential to the definition of the models. These include the knowledge of many diverse components such as the earth gravity field, the earth deformations and mapping of geological structure, the ocean global circulation and the ocean-atmosphere coupling, and the atmosphere energy budget and radiation transfer. Clearly, a global understanding of the various physical components and their interrelationships is a prerequisite to the understanding of the evolution of the planet Earth.

The direct exploration of the solar system with the possibility of in situ measurements of the other planets and their atmospheres and magnetospheres is also providing information which is extremely valuable for the understanding of the history and evolution of our own planet.

In addition, access to the environment of other planets, coupled with in-depth studies of Earth phenomena and with theoretical models, is crucial to the understanding of the detailed balances which maintain the climatic system of the Earth.

1.6 The overall European Long Term Programme in Space Science

(Astronomy, Planetary Research, Space Plasma Physics, Solar and Heliospheric Physics)

1.6.1 Further criteria

The survey Committee followed the criteria established in para. 1.3, plus these additional factors:

i. the scientific community responded significantly to the Call for Mission Concepts; a sure sign of the importance of the ESA science programme in the eyes of European scientists;
ii. the proposals received covering the entire spectrum of the scientific disciplines under consideration;
iii. the future global programme should be specific in the identification of the major thrusts, show coherence, and be feasible within a 20 year period;
iv. the future programme should be contained within a new budget envelope of about 200 MAU's a year in 1983/84 financial conditions, to be reached progressively between 1985 and 1991, i.e. an increase of 50% over the 1984 level of about 130 MAU/year.

Various considerations support the establishment of this new level. From a scientific viewpoint, this new level will permit the essential major projects which cost in the order of two annual budgets, to be identified in advance. At the same time a reasonable number of medium and small size projects will be maintained. Furthermore, industry has independently arrived at the same figure, based on its concept of a reasonable frequency of development contracts for the European consortia (Eurospace 'Proposals for a European Long-Term Space Programme', May 1984). Moreover, it should be noted that, under the hypothesis of a 50% increase of the overall Agency budget to include the new large inititiatives in the domain of transportation systems and manned space station, this new level would maintain the science programme in the same ratio to the overall Agency budget as at present.

1.6.2 Programme Elements

The overall programme proposal is represented in Fig 00. It is founded on four major programme elements, identified as the 'four cornerstones', with a time schedule extending to 2004, satisfying the highest priorities in the domains of solar system sciences and astronomy. Of these four elements, two are in the solar system sciences:

- planetary exploration
- solar terrestrial physics

and the other two are in astronomy:

- X-Ray spectroscopy
- heterodyne spectroscopy.

Three of the four cornerstones, consist of single projects costing about 400 MAU each, within the ESA framework. Furthermore, a number of medium (about 200 MAU) and small (about 100 MAU) projects are included in the overall programme.

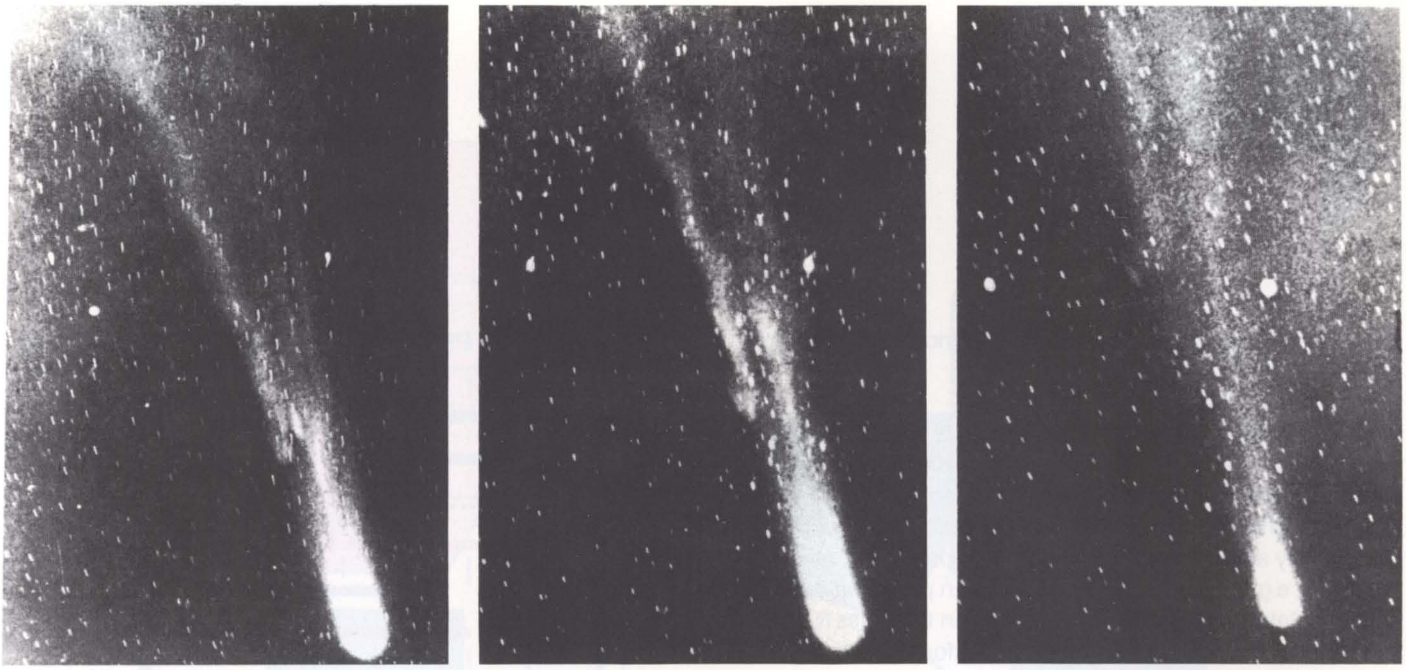
The four cornerstones are:

The Solar Terrestrial Programme (STP)

The STP relies on the large European experience in solar, heliospheric and space plasma physics. It will attack the outstanding scientific problems in these fields in a unified and well-coordinated approach. This cornerstone consists of two medium-size projects – an observatory in the L_1 Langrangian point and a multipoint space plasma physics mission. A special effort will be required to prepare for the operations and data handling of multi-spacecraft missions.

A Mission to Primordial Bodies including Return of Pristine Materials

Within planetary exploration, this is an area where Europe could take the lead, following on the Giotto mission. The return of primordial material from primitive bodies, namely from asteroids and comets, constitutes a major theme in future planetary science. In the case of asteroidal samples, this would lead to a direct comparison with meteoric materials at the accuracy levels of a few parts in a thousand for elemental and isotopic composition, as required for classifying the material. A returned drill core from a comet, consisting of ice and dust, would be of the highest scientific interest. A cometary sample might contain not only unaltered pristine solar system material,



One of the best recorded primordial bodies in the solar system. Time sequence photography of Halley's Comet, 6-7 June 1910

but possibly also interstellar and stellar material ('star dust'). This would give essential insight into the physics and chemistry of the star formation region. A joint ESF/NAS Working Group for planetary exploration also identified this mission as one of high priority.

A High Throughput X-Ray Mission for Spectroscopic Studies between 0.1–20 keV

The observatory, comprising multiple telescopes, provides the required sensitivity to perform detailed spectral diagnostics of many classes of objects with low (surface) brightness. This is particularly important for studying the evolution of the large and small scale structures of the Universe. It further allows simultaneous observations of several characteristics of astronomical objects and thereby to achieve a much better understanding of the ongoing physical processes. It is an ideal complement to the AXAF (NASA) mission, which pursues ultimate imaging capabilities with primary emphasis on deep surveys.

A High Throughput Heterodyne Spectroscopy Mission

The sub-mm domain is the last remaining gap in the electromagnetic spectrum left unexplored. Apart from the continuum radiation from dust, this range also contains a large number of very important atomic and molecular transitions which provide a direct probe for studying the physics and chemistry of the cool universe in the range 3–1000 K. A major mission in this area is thus of the highest scientific importance and would exploit in an optimum way European developments in the area of sub-mm antennae and heterodyne receivers.

These four cornerstones and related major projects need to be identified early because of the long lead time connected with their implementation. They thus constitute the basic framework for future activity in Europe and introduce a crucial solidity in the construction of the overall programme.

As a follow-up to these four elements it is already possible to identify beyond the horizon 2004 other major thrusts: these are the Solar Probe and the Heliosynchronous Out of Ecliptic Mission in solar terrestrial physics, the Mars Rover in the planetary area, and, in astronomy, two-dimensional interferometry for high spatial resolution in the visible, infrared (IR) and millimetre (mm) wavelength region. These thrusts are beyond the present programme, for technological and financial reasons, as their inclusion within the horizon 2004 would require funds in excess of the self-imposed limit of 200 MAU/year. However, some of these projects could be brought within the proposed long term programme, if additional funds could be made available in the frame of cooperative projects.

On a smaller scale, a number of the conventional medium-size projects, costing about one annual budget each (~200 MAU), will be realised in the same time frame. They include projects already approved: Giotto, Ulysses, ST, Hipparcos and ISO, and about five more such projects. The Mission Concepts addressed to ESA contain a number of possible candidates, including: planetary orbiters, solar telescopes, plasma and auroral projects, UV spectroscopy complementary to ST, stellar seismology missions, and cm-VLBI radio astronomy. These projects will be selected according to the ESA science programme's standard procedure, i.e. through an open competitive selection. Through this procedure, the overall programme regains its required flexibility and its capability to meet the shifting needs of science.

On a still smaller scale, a number of projects are included in the programme each costing not in excess of 100 MAU. They respond to the need, established in the scientific chapters, for frequent flight opportunities, for quick reaction to missions of opportunity and for minor participation in projects of other Agencies, e.g. a Titan probe as a European participation in a possible Saturn Titan mission. Prominent in this class is a programme making use of retrievable platforms such as Eureca, which is presently being developed within the microgravity programme, and which could be suitably modified to meet the requirements of astronomical and solar physics payloads. This is particularly important for X and gamma-ray astronomy payloads, for solar physics and for UV and visible astronomy. The mission and payload selection in this class will also follow the conventional competitive selection procedure as at present.

Also included in the programme is the development of the technologies which are needed for the cornerstone missions and even the later missions.

The entire programme can be realised in the horizon 2004 within a new budget envelope of 200 MAU a year, to be reached progressively between 1985 and 1991. This is demonstrated here as one of a family of curves which also shows how budget residuals vary around the budget reference level with varying sequences of large, medium and small size projects. Underruns and overruns can never be avoided in a fixed budget situation, a feature to be accepted to allow an optimisation of the financial management of the programme.

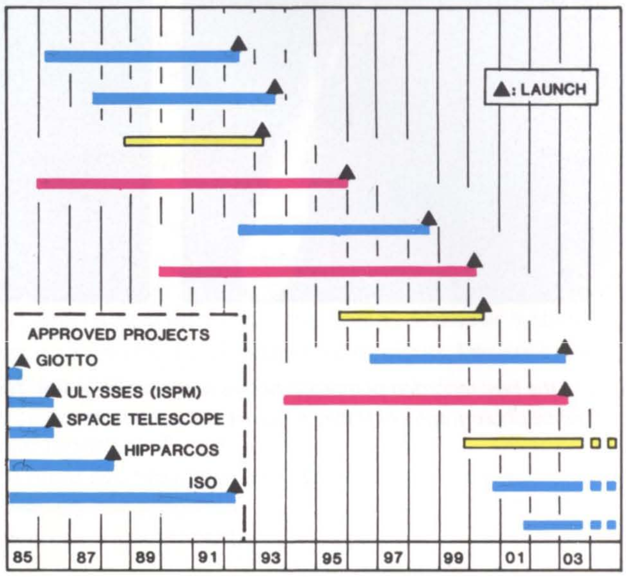
1.6.3 The programme and its relation to other Agencies programmes

Although the four 'cornerstones' are basically within Europes capability to achieve, they would benefit from a timely coordination with related projects in other Agencies. This is particularly true for STP which would be part of the International Solar Terrestrial Programme (ISTP) with the USA, Japan and possibly the USSR, and other nations.

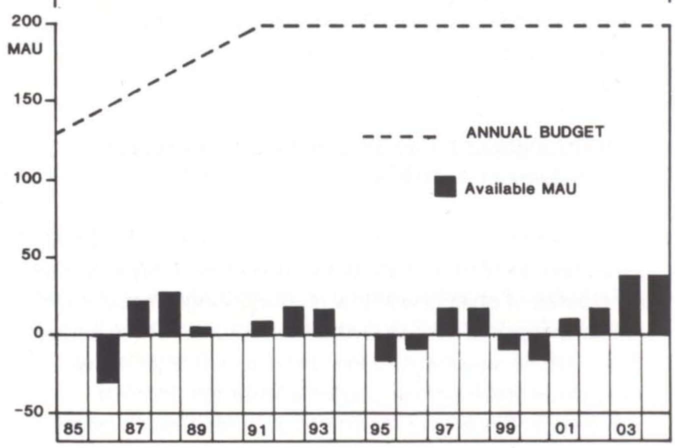
Furthermore, the solar terrestrial physics and planetary science 'cornerstones' are highly relevant to the worldwide International Geosphere-Biosphere Programme (IGBP) presently under active definition, and to studies of the Earth as a planet.

Similarly, the High Throughput X-Ray Spectroscopy project would benefit from coordination with the NASA AXAF project, while the Heterodyne Spectroscopy project is a precursor to the Large Deployable Reflectors presently being considered by other Agencies.

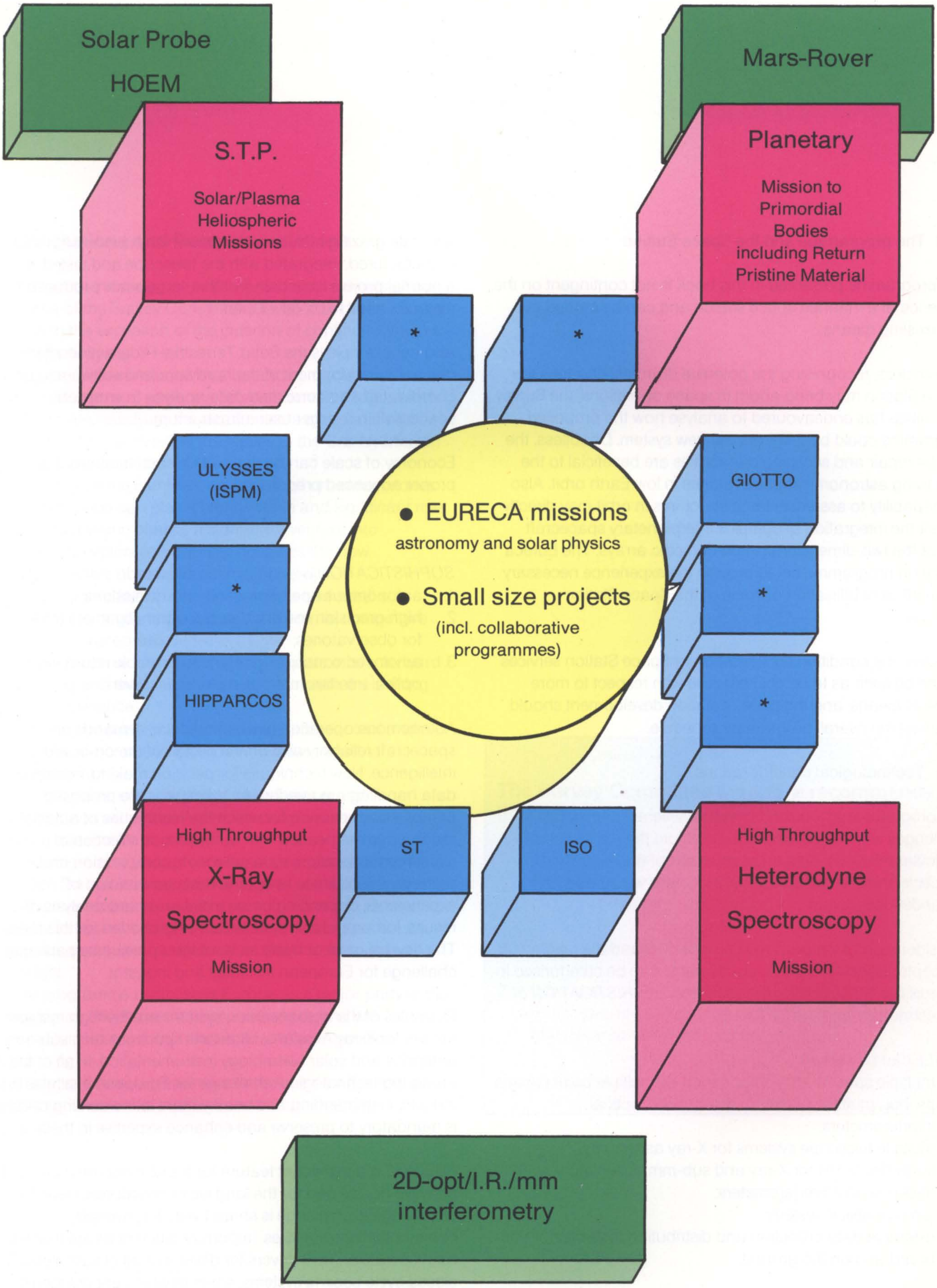
SCIENTIFIC PROGRAMME SURVEY 1985–2004



SCIENTIFIC MISSIONS SURVEY 1985–2004 BUDGET RESIDUALS



A continuation of existing forms of coordination and cooperation is foreseen for medium size projects. Joint efforts are not excluded for small-size projects. Utilisation of Eureca, for example, would provide such an opportunity. European institutes could find it difficult both to provide the funding or develop the instrumentation to make full use of Eureca's capacity (1 ton), and at the same time respond to flight opportunities at reasonable frequencies. A satisfactory programme could be possible, however, by sharing the Eureca facility with US and other Agencies.



The European Long Term Programme

[*e.g. : - Solar Heliospheric (Soho), Multipoint Probes (Cluster), Auroral Multiprobes, etc., in Solar/Heliospheric/Plasma Physics; - Venus (Venture), Mars (Kepler), Lunar (Selene) Orbiters, etc., in Planetary Science; - Space VLBI, UV Spectroscopy, Stellar Seismology, etc., in Astronomy.]

1.6.4 The programme and the Space Station

The programme presented in this book is not contingent on the existence of a manned space station and can be carried out with existing means.

Nonetheless, recognising the potential dramatic changes the Space Station may bring about in space operations, the Survey Committee has endeavoured to analyse how the proposed programme could benefit from the new system. Doubtless, the in-orbit repair and servicing capabilities are beneficial to the long-living astronomical observatories in low Earth orbit. Also the capability to assemble large structures in orbit may directly benefit the integration of complex interplanetary spacecraft and of the two-dimensional interferometric arrays. The Eureca utilisation programme could provide the experience necessary for an efficient utilisation of some of the Space Station elements.

However, the conditions of utilisation of Space Station services should be such as to be cost effective with respect to more classical means, and the pace of station development should not affect the overall programme schedule.

1.6.5 Technological considerations

The programme as outlined presents several technical challenges which must be resolved before the realisation of particular missions. Also an assessment of the mission concepts showed that about 30% of these would need advanced technology.

Consideration of the proposed programme and the mission concepts suggests that the requirements can be categorised in terms of the *SCALE* of the missions, the *SOPHISTICATION* of the technology and the *LIFETIME*.

SCALE can be seen in:

1. multiple spacecraft missions such as multiple point plasma probes, multiple planetary orbiters and optical interferometers;
2. multiple telescope systems for X-ray astronomy;
3. large structures for X-ray and sub-mm observatory missions and interferometers;
4. ion propulsion system;
5. extensive data collection and distribution systems both on-board and on the ground.

The technical challenge of these lies in the development of techniques that allow the procurement of the missions in an acceptable timescale and cost. A specific example is the manufacturing of mirror systems for high throughput X-ray spectroscopy missions. Such missions need many hundreds of separate grazing incidence mirrors which have to be manufactured, integrated with the telescope and tested within a normal project timescale. For this, large scale production methods need to be developed.

Another example is the Solar Terrestrial Programme which demands development of the hardware and software to allow coordinated and correlated data analysis from several spacecraft in a larger user infrastructure.

Economy of scale can be realised for such missions if given proper advanced preparation.

SOPHISTICATION is evident in the need for:

1. autonomous operation of planetary missions;
2. high precision mirrors, detectors and alignment systems for observatories;
3. advanced concepts for planetary sample return missions, optical interferometry and planetary rovers.

Autonomous operation places particular demands on spacecraft reliability and on the design of the on-board intelligence. New techniques for decision making, control and data handling are needed. An example is the proposed primitive body mission for which the techniques of autonomous rendezvous are needed with autonomous selection of experiment operation, data collection, compression and, perhaps, the ability to select the best combination of experiments, depending on an initial on-board analysis of results. Ion propulsion systems are also needed for this mission. The development of these technologies presents a particular challenge for European institutes and industry.

Examples of the high precision systems are the high resolution mirrors for X-ray missions, ultraviolet spectrometers, sub-mm antennas and solar seismology instrumentation. In all of these areas, the technological challenge for European institutes and industry is demanding and commitment in the coming decade is mandatory to preserve and enhance expertise in these areas.

LIFETIME is a signficant feature for the planned missions to the primitive bodies and for the long life observatories. Here, the technological challenge is shared with, for example, communications satellites. Important differences are that the science missions are drivers for development of such items as closed cycle cooling systems, some of which are cryogenic, and for long lifetime sophisticated electronic systems which may have fault detection and correction capability. The IR and sub-mm astronomy missions and the planetary missions will require the output from such technology.

1.7 Conclusions and Recommendations

- In essence the programme presented above meets all the criteria of the Survey Committee identified in paras 1.3 and 1.6 with the exception of the criterion of continuity which is only partially met.
- the programme includes, in a balanced manner, all the major domains of science in ESA's Scientific Programme Directorate, satisfying the requirements of the scientific community, expressed in the replies to the Call for Mission Concepts and other inputs.
- The programme identifies, and is based on, cornerstones where Europe can play a highly visible and significant role.
- The programme permits a significant venture into planetary exploration and also includes the now indispensable observatories in astronomy.
- The programme also includes medium and small size missions to be identified through the normal competitive selection procedure.
- The programme blends the rigidity intrinsic in any forward planning with the flexibility required to match the shifting needs of science.
- The programme has a high technological content and provides major challenges for innovative industrial development.
- The programme lends itself to coordination and cooperation with other Agencies' programmes while not being dependent on them.
- The programme, though not contingent on a manned Space Station, can take advantage of some elements of it.
- The programme represents a quantum jump in Europe's ability to be at the forefront of all domains of space science at a cost of a relatively modest increase in the budget.
- The programme establishes Europe as a major party in the worldwide development of space science and will constitute an essential reference for other Agencies' planning.
- The programme is responsive to the need for Europe to honour its scientific tradition and cultural heritage.

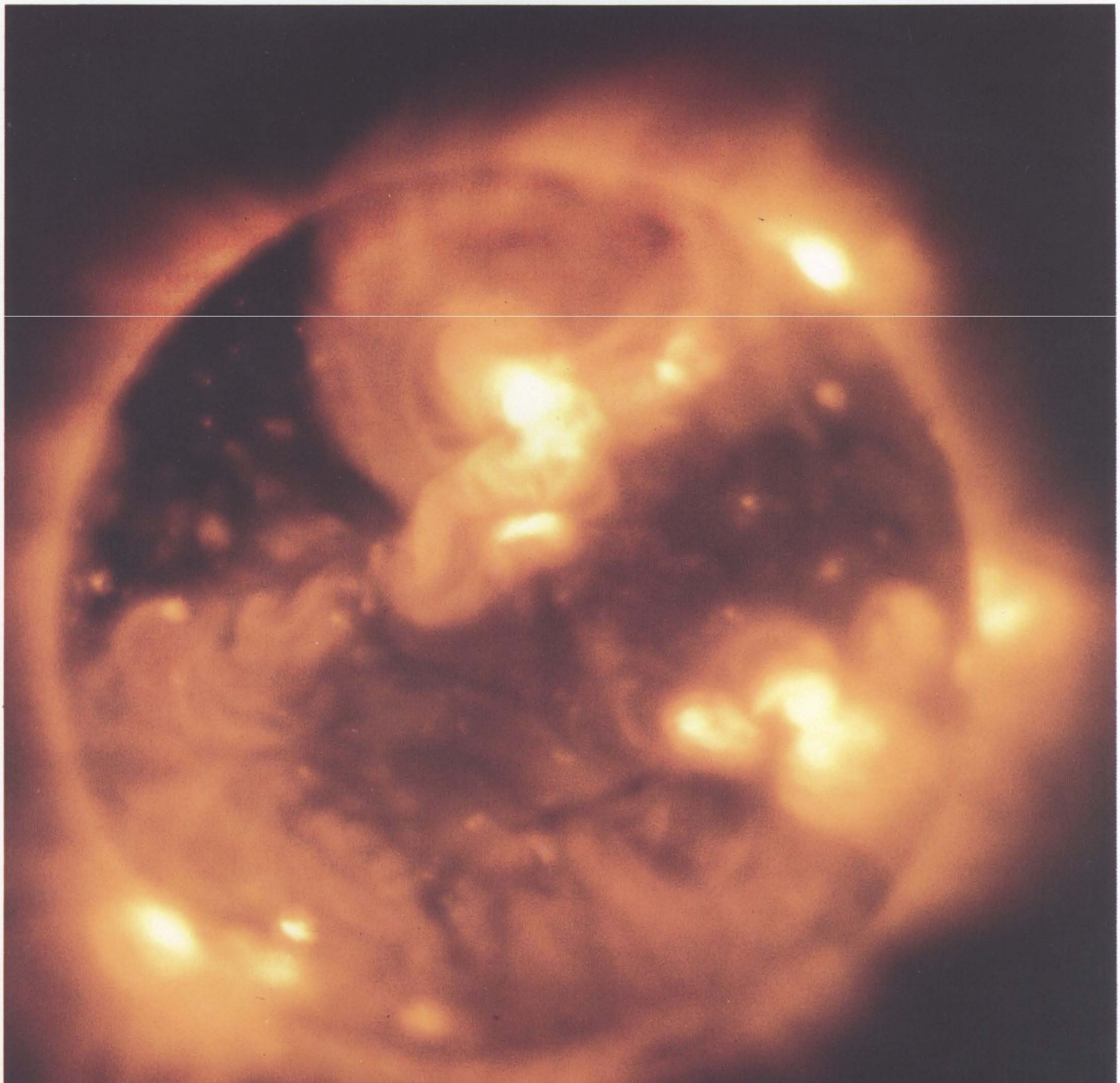
The Survey Committee therefore recommends that:

1. The programme presented in this paper, based on the four essential cornerstones and further medium and small size projects, be approved for realisation by the year 2004;

and, as a consequence, that:

2. the mandatory space science budget for solar system sciences and astronomy be set at the new level of 200 MAU/year at 1983/84 financial conditions.

Part 2 – Solar System Science



THE ASCENDING CYCLE. Eighteen Months after Solar Minimum Activity Begins to Build in the Solar Atmosphere. Note the Bright Active Regions with their High Loop Systems at Both Limbs in this X-Ray Photograph Taken from a Sounding Rocket on January 31, 1978.

The Solar Physics Group, American Science and Engineering, Inc., Cambridge, Mass.

2. Solar System Science – Survey Committee Report

The solar system provides a vast laboratory for mankind to gain insight into many basic processes. The advent of satellites has revolutionised such disciplines as solar and heliospheric physics, space plasma physics, and planetary science. The programme includes two major elements which will continue the exploration of the solar system, and in particular will build on the lead established with the Giotto and Ulysses missions.

2.1 Solar System Science

The solar system is our cosmic habitat – a most important sample of the universe on our doorstep. Here, the techniques of space research enable us to explore celestial bodies and their environment by satellites and probes that can take close up images and measure physical parameters in situ; an example is the eagerly awaited Giotto probe that will encounter Comet Halley in 1986.

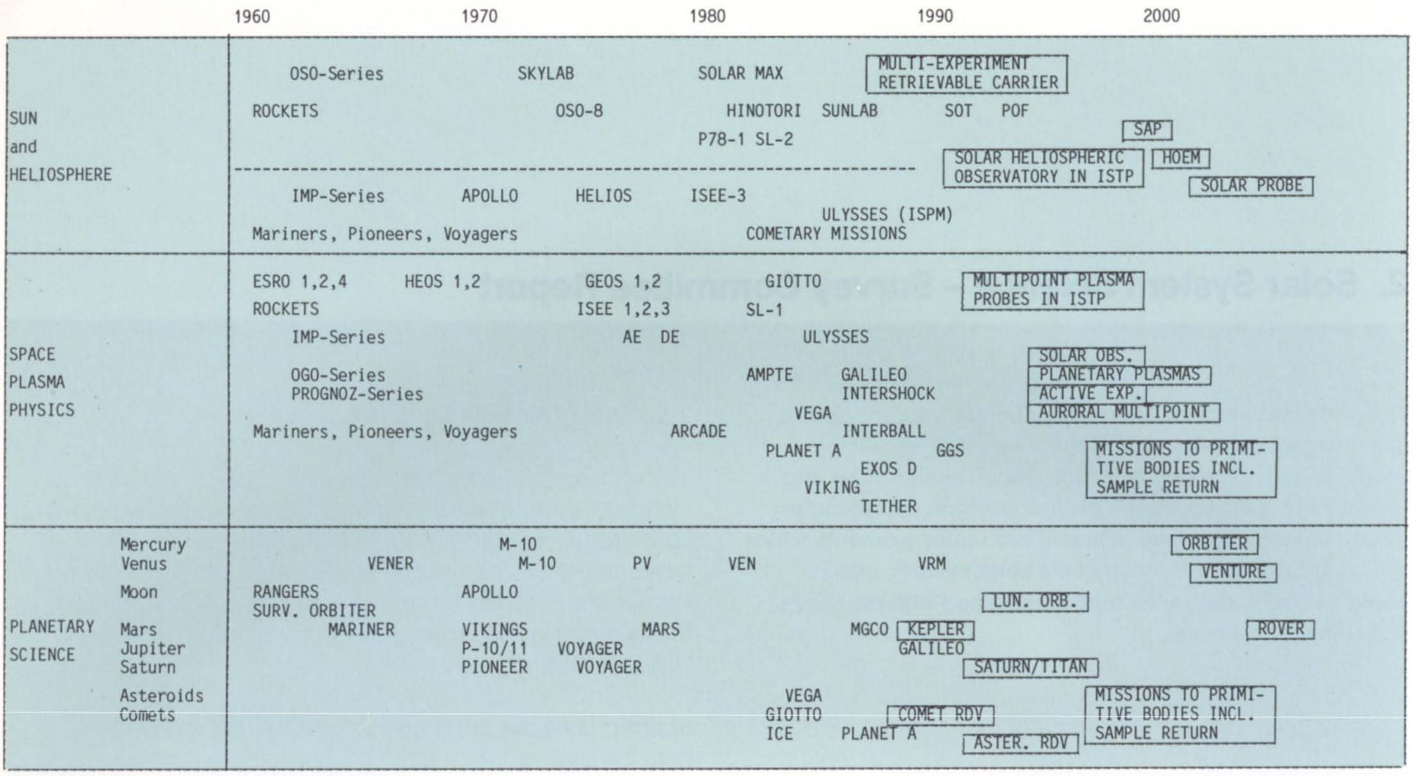
Space probes can fly by, go into orbit around and descend onto the planets, their moons, the asteroids and comets – and even bring back samples from these bodies. Thus, in addition to specifically space-oriented techniques, many highly developed scientific methods belonging to hitherto Earth-bound disciplines, such as, for example, geology, geophysics, aeronomy, climatology and meteorology, can be brought to bear on the riddles of the solar system and its evolution.

Satellites orbiting in the Earth's neighbourhood can sample the interactions between magnetic fields and electrically charged particles, i.e. plasma processes, by highly detailed in situ measurements, and so this vast laboratory can be used to gain insight into basic plasma physics processes.

Further away from the Earth, in situ measurements permit direct determination of the chemical and physical properties of the highly variable particle streams emanating from the Sun – the solar wind. In addition, our moderate distance from the Sun, eight light minutes, means that its diameter subtends a sizeable angle (half a degree) on the sky. This allows imaging and thus it is possible to observe directly and study from near-Earth space, at all wavelengths of the electromagnetic spectrum, the physical properties of the plasma structures that make up the dynamic atmosphere of our daylight star.

Generally, missions within the solar system can also provide platforms for experiments testing the theory of gravity (general relativity) and searching for gravitational waves. The scientific aspects of this field are presented in Part 3 – Astronomy.

Solar system science comprises the investigation not only of the components per se – the Sun, the space plasma, the solid bodies and the atmospheres – but also the study of the sometimes subtle interactions between its components. Indeed, interactions are of particular interest, as they are often intimately connected with the evolution of the solar system.



Missions in Solar System Science

2.2 Overview, outstanding problems

a. Solar and heliospheric physics

The Sun, which forms the centre of the solar system, nurtures all life on Earth. It is the principal source of energy in the solar system and has a rapidly expanding outer atmosphere, which fills the entire solar system – the heliosphere – and constitutes the dynamic interplanetary medium. The latter in turn interacts with the planetary bodies.

The study of the Sun and heliosphere and their interplay with the planetary system is the domain of solar and heliospheric physics. This field of research has witnessed a revolutionary expansion over the last 20 years with space observations bringing decisive advances in our knowledge. The Sun- and heliosphere provide the yardstick by which the behaviour of other stars in the Universe and their sphere of influence can be compared. Of particular importance are:

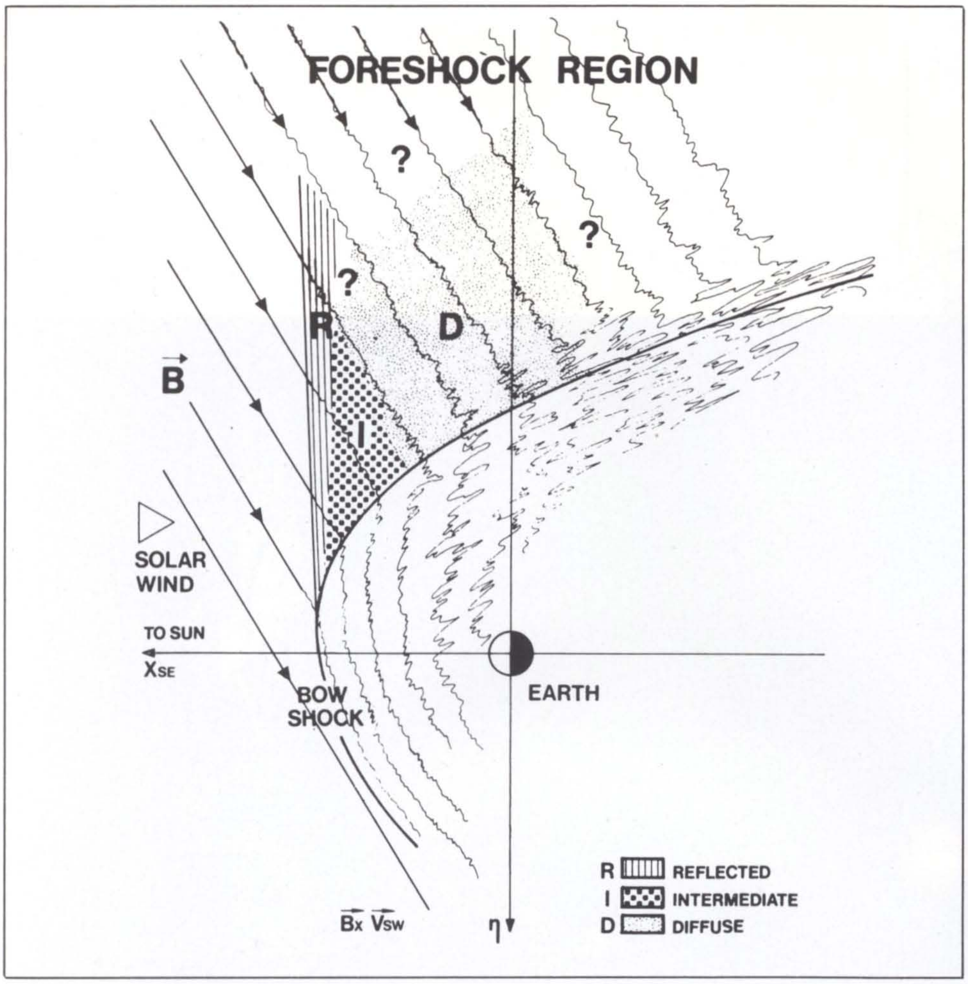
- calibration and testing of stellar evolution scenarios and calculations. The last decade has witnessed the first detections of solar neutrinos, and the discovery of global solar oscillations which has led to the development of the field of helioseismology: for the first time, we can start 'seeing' the interior of a star.
- the study of the properties of magnetic fields interacting with plasmas of astronomical size. This problem is still not well understood. It is theoretically very difficult and laboratory experiments are not feasible. The unique opportunities provided by the Sun and the solar system as gigantic laboratories have been well exploited with the advent of the space era. It is now realised that for example the origin of the enigmatic coronal heating must be sought in the magnetic field. However, despite intensive theoretical and observational work, no specific mechanism has yet been identified.
- the phenomenon of mass-loss. Mass-loss is a common phenomenon in the Universe. Most stars show it and probably also the galaxies. An important problem, most efficiently tackled by solar heliospheric studies, is the question how slow-speed streams can emanate from an apparently closed magnetic structure.
- acceleration phenomena in shocks. This is another fundamental problem in modern astrophysics. Here the so-called solar transients, shocks propagating through the solar wind and the Earth's bow-shock, provide nearby objects for study.

In summary, solar and heliospheric physics are not only of fundamental importance for general astrophysics, but also for basic areas such as magnetohydrodynamics, plasma physics, atomic physics and particle physics.

b Space Plasma Physics

Space plasma physics explore the heliosphere, and the magneto- and ionospheres of planetary bodies, including the Earth. It is the goal of space plasma physics to interpret the sometimes very complex phenomena observed in these objects, in terms of basic plasma physic processes, that are relevant to the entire Universe. Plasma investigations take on different forms: the classical methods are in situ measurements and active experimentation (where the natural state of a plasma is perturbed by artificial injection of particles or waves). Solar plasma physics relies to a large extent on astronomical techniques (i.e. on spectroscopic observations). Because it permits high spatial resolution observations it provides the link between space plasma physics and the wide field of plasma astrophysics.

The advent of space exploration has expanded our knowledge



Illustrating where ions are sent from the Earth's bowshock region back towards the sun and along the magnetic field lines. R (reflected), I (intermediate) and D (diffuse) represent characteristics of the ions found in different regions

and understanding of natural plasmas considerably, both on the macro- and the microscales. Configurations such as magnetospheres with extended tails, interplanetary sector structures, collisionless shocks, ionopauses at the interface of the solar wind and a non-magnetised ionosphere were phenomena unknown before the space age. Perhaps even more exciting are the dynamic processes playing inside these systems or at critical interfaces. For example, one of the fundamental modes of converting mechanical energy first into stored magnetic energy and releasing it subsequently in a variety of forms including beams of high energy particles, fast plasma convection, radio bursts, etc. is the geomagnetic substorm.

The study of space plasma physics is often complemented by investigations in laboratory plasma physics and by numerical simulations, and there is a steady cross-fertilisation between these methods.

Although a rich harvest has expanded our knowledge of fundamental interaction processes of cosmical plasmas, many open questions and also largely unknown areas remain: as examples, cometary interactions, dust dominated plasmas, and turbulent magnetohydrodynamic flows can be mentioned.

c Planetary Science

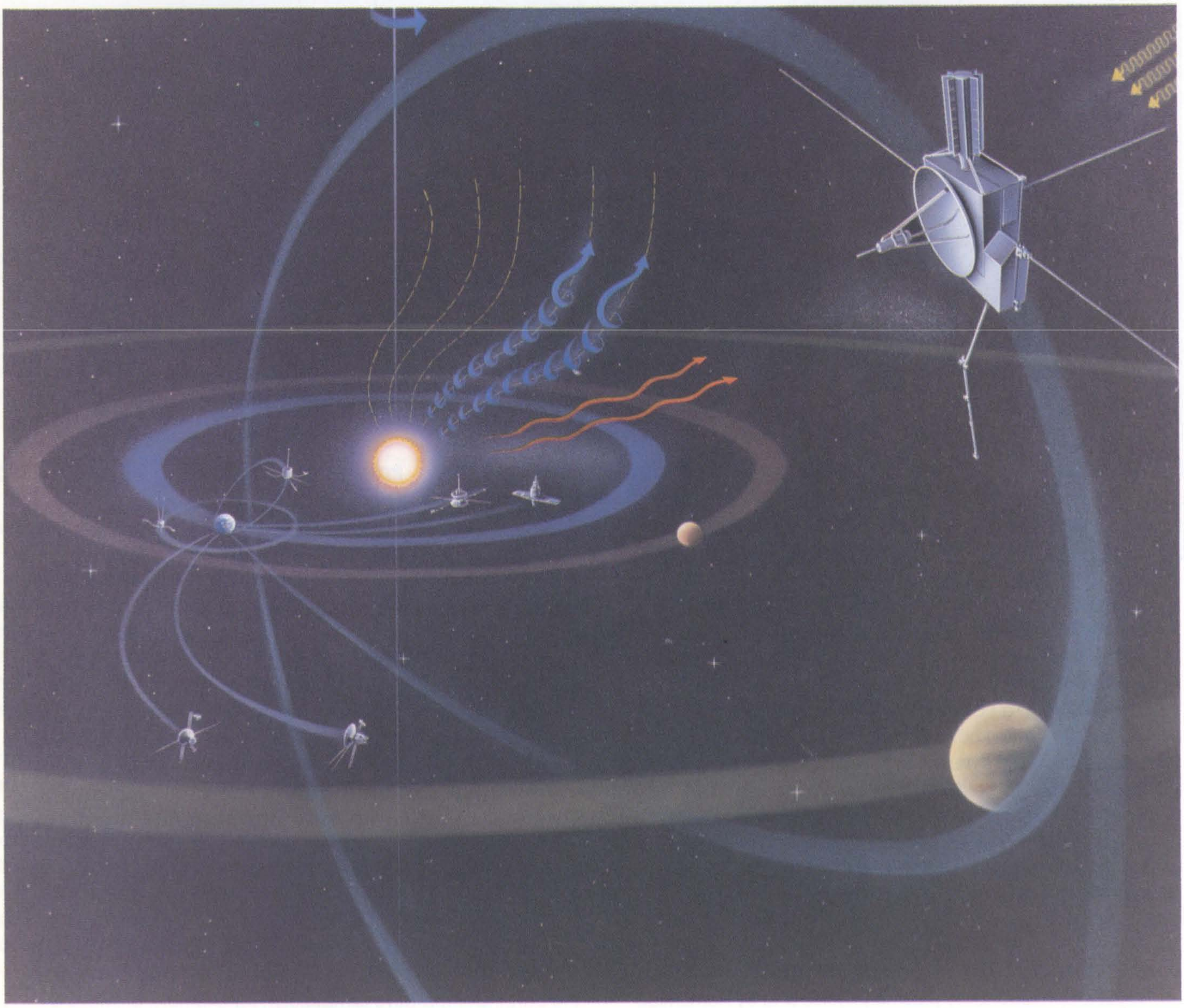
This field not only covers the study of the solid bodies in the solar system, but also their surfaces, atmospheres and plasma environments and the causes and effects of their mutual interactions.

The study of various bodies in the solar system will shed light on the origin and evolution of our solar system. These bodies range from those which are nearest their origin composition such as comets, asteroids and the outer planets, to the much more evolved inner planets. They exhibit a wide variety of different physical properties and processes with regard to their composition, surfaces, atmospheres and their plasma environment. It is the aim of planetary science to study this complex multitude with a view to learning not only about these bodies and the origin and evolution of the solar system, but also about the unique role of our planet Earth as an abode of life.

The comparison of solar system objects is a very fertile ground for study, that is the comparison between different planets and the Earth. Comparative climatology, for example, provides a broad context, in which we can view the familiar and intimately known phenomena and processes on Earth. A practical aspect of such studies is that they provide the understanding necessary for evaluating consequences of natural or anthropogenic perturbations on our atmosphere, environment and ecological system.

Apart from the need for more sophisticated studies with the aid of orbiters around Mercury, Venus, Mars, Saturn and other planets, multiple rendezvous with small bodies (asteroids and comets) including return of pristine material constitute a major theme in future planetary science. In the case of asteroidal samples, this would lead to a direct comparison with meteoric material at the accuracy levels of a few parts in a thousand for elemental and isotopic composition which is required to

Ulysses (ISPM)

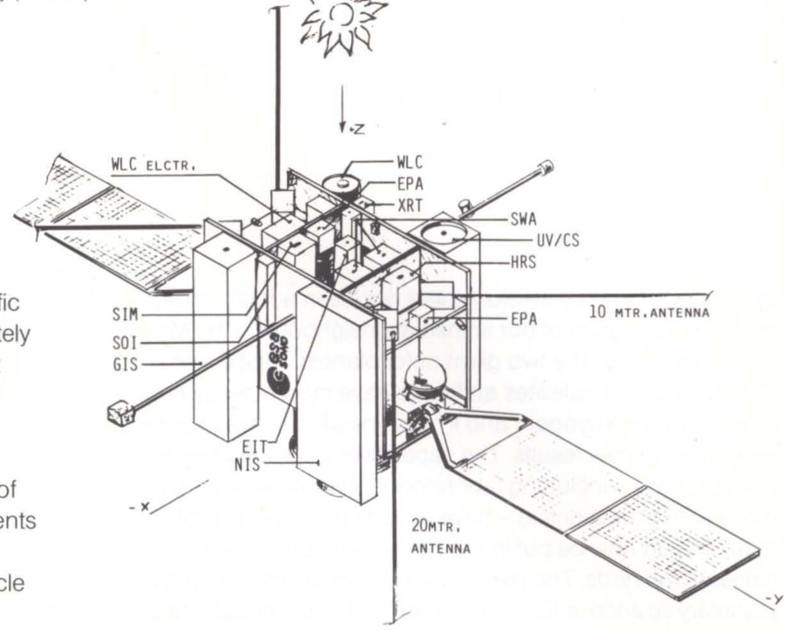


classify the material. A returned drill core from a comet, consisting of ice and dust, would be of the highest scientific interest, since it might contain not only unaltered pristine solar-system material, but possibly also interstellar and stellar material ('star dust'). This would give essential insights into the physics and chemistry of star formation regions.

2.3 Mission Concepts, Identification of Programmatic Elements

The history of space missions addressing topics of *solar system science* is shown on page 20. In the discipline of solar physics, early rocket flights – starting already in the mid-forties – were followed by the Orbiting Solar Observatory (OSO) series, the Apollo Telescope Mount on Skylab, and specialised flare investigations, the Solar Maximum and the Hinotori missions. Currently, solar Spacelab payloads are being planned in the US, in particular Sunlab, the Solar Optical Telescope (SOT) and the Pinhole Occulter Facility (POF). Significant experiments in heliospheric physics were performed early on from Interplanetary Monitoring Platforms (IMP) and during the Apollo Moon landings, and later, on the German Helios Mission as well as on the Geos and ISEE-3 satellites. Further investigations in heliospheric physics will result from the various missions to Comet Halley, including Giotto, and from the Pioneer and Voyager probes and, most important, from Ulysses, formerly called the International Solar Polar Mission (ISPM).

The Solar and Heliospheric Observatory (SOHO)



An analysis of these missions shows that most of the scientific needs for solar and heliospheric physics will not be adequately satisfied. In particular the following fundamentally important science will not be addressed at all: helioseismology, measurements of coronal magnetic fields, coronal imaging beyond ten solar radii, concerted solar and heliospheric observations, advanced plasma physics, stereoscopic view of solar structures, synoptic view of the Sun, in-situ measurements in the corona (inside about sixty solar radii) and long term observations (for any of these topics) to investigate solar cycle variations.

A long range programme that would fulfill scientific needs, including the above-mentioned 'gaps', comprises five basic elements, i.e.

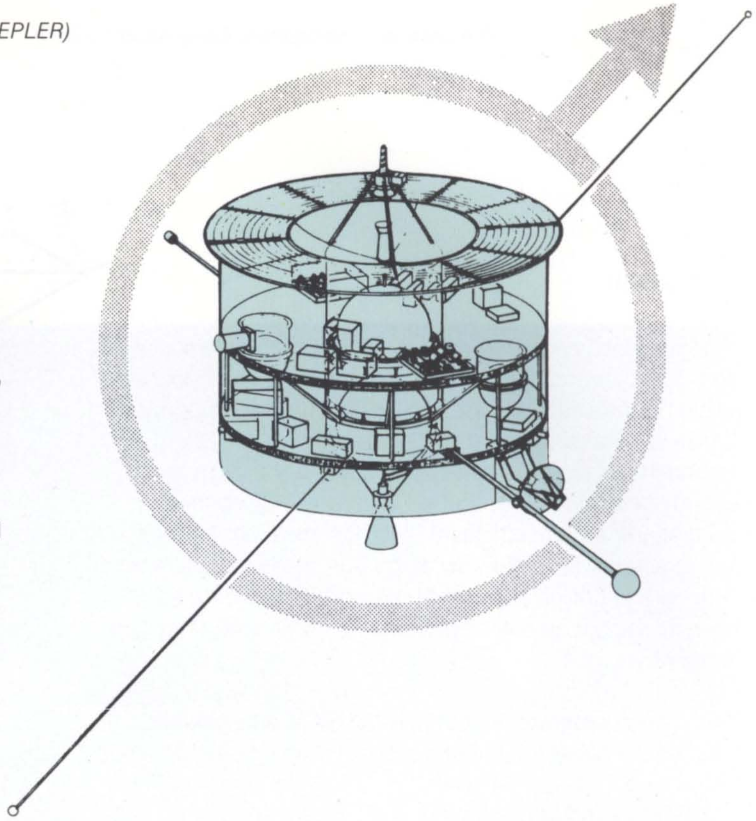
- Free-flyer in Earth orbit.
  Main topics which will be addressed are: ultrahigh spatial resolution (subarcsec), concerted imaging and spectrometry in many wavebands simultaneously.
- Lagrangian point L1 observatory.
  Main topics which are addressed: helioseismology, continuous in-situ measurements of the solar wind, continuous coronal diagnostics. The Solar Heliospheric Observatory, which is currently in the Phase A study stage, belongs to this category, and could be part of the International Solar Terrestrial Physics (ISTP) Programme.
- Continued colonisation of the L1 Lagrangian point on the Earth-Sun line as part of a Synoptic Array Programme (SAP) an array of four spacecraft in solar orbits in the ecliptic plane at position angles 0° (L1 point), 90°, 180° and 270°).
  Synoptic coverage addresses: global magnetic field modelling, evolution of global structures, correspondence between solar structures and near Earth events, stereo view of coronal structures, magnetic fields, direction of particles and flares.
- Heliosynchronous Out-of-Ecliptic Mission (HOEM).
  A satellite at a solar distance of about 30 $R_{\odot}$ quasi synchronous with the solar rotation period. The main topics addressed by this mission comprise: detailed study of the evolution of solar structures and solar wind from a point close to the Sun, in-situ sampling of a wide latitude range in a short time period, frequent good coverage of the polar regions of the Sun, a stereoscopic view.
- Solar probe.
  The Solar probe would have a perihelion distance of a few solar radii in an orbit which may be out of the ecliptic. Main topics include in-situ measurements in the solar corona down to the regions where much of the solar wind acceleration takes place, determination of the solar gravity field and testing of General Relativity.

Space plasma physics, is an example of a field that is entirely dependent on space techniques. Modern space plasma physics projects should be seen in the context of the past missions shown on page 20: in addition to a large number of sounding rocket experiments, several Orbiting Geophysical Observatories (OGO) and Prognoz satellites have been flown. The Heos, Geos and ISEE missions provided further, significant advances. AMPTE, Giotto and Ulysses (ISPM) will be the next milestones with substantial or dominating European contributions, and a number of smaller national programmes as, for example, Viking, Vega, Interball, EXOS-D, testify to the vigorous activity in the field of space plasma physics. Over the last twenty years, the discipline of space plasma physics has reached a degree of maturity where demands on spacecraft sub-systems and measurement techniques will be specified very precisely as each step of improved understanding is made. Also, the regions of space in which to conduct investigations will have to be carefully selected. Programmatic elements comprise:

- The Earth's readily accessible plasma environment will have to be exploited further for basic plasma physics investigations. The next major step here is a multi-point mission such as the Cluster project, which is currently in a Phase A study stage and also represents the basic plasma-research mission of the International Solar Terrestrial Physics (ISTP) Programme.
- In other cases, it is possible to share spacecraft and flight opportunities with other disciplines in solar system science, notably with planetary missions since there is the need to study other plasma systems (i.e. near other planets) where factors governing the behaviour of plasma differ significantly from those existing near the Earth.

Planetary science is also almost entirely dependent on the data acquired by space research. During the past two decades, spacecraft from the US and USSR have explored our solar system from Mercury to Saturn. Planetary missions have ranged from fly-bys to landings, and orbiting satellites. There have been considerable differences of effort put into exploration of the various planets. While Mercury has only been

A Mars orbiter mission (KEPLER)



studied by one fly-by mission, there has been a much more detailed exploration of our immediate neighbours – the Moon, Venus and Mars. The two giant outer planets, Jupiter and Saturn, and their satellites and rings have most recently been covered by the Voyager-I and II missions which have provided most exciting new results. The capabilities of ground based investigations – including laboratory studies of extra terrestrial material (e.g. meteorites) – have already been well exploited. Effort should now be put in planetary studies by space research methods. The new mission concepts proposed for planetary science in Europe include the following elements:

- a Mars orbiter mission (e.g. the Kepler project)
- a Lunar orbiter
- a comet fly-by mission
- multiple Venus orbiters.

A set of more advanced missions include:

- a Mercury orbiter
- a Saturn Orbiter/Titan Probe mission (the Cassini project)
- a multiple small bodies rendezvous mission (asteroids and comets)
- a comet nucleus sample return mission
- a Mars Rover mission.

Three of the above missions were identified by the ESF/NAS Joint Science Working Group on Planetary Exploration; joint ESA/NASA assessment studies on a multiple primitive bodies rendezvous mission and the Saturn Orbiter/Titan Probe mission are currently in progress.

2.4 Solar System Science Community in Europe

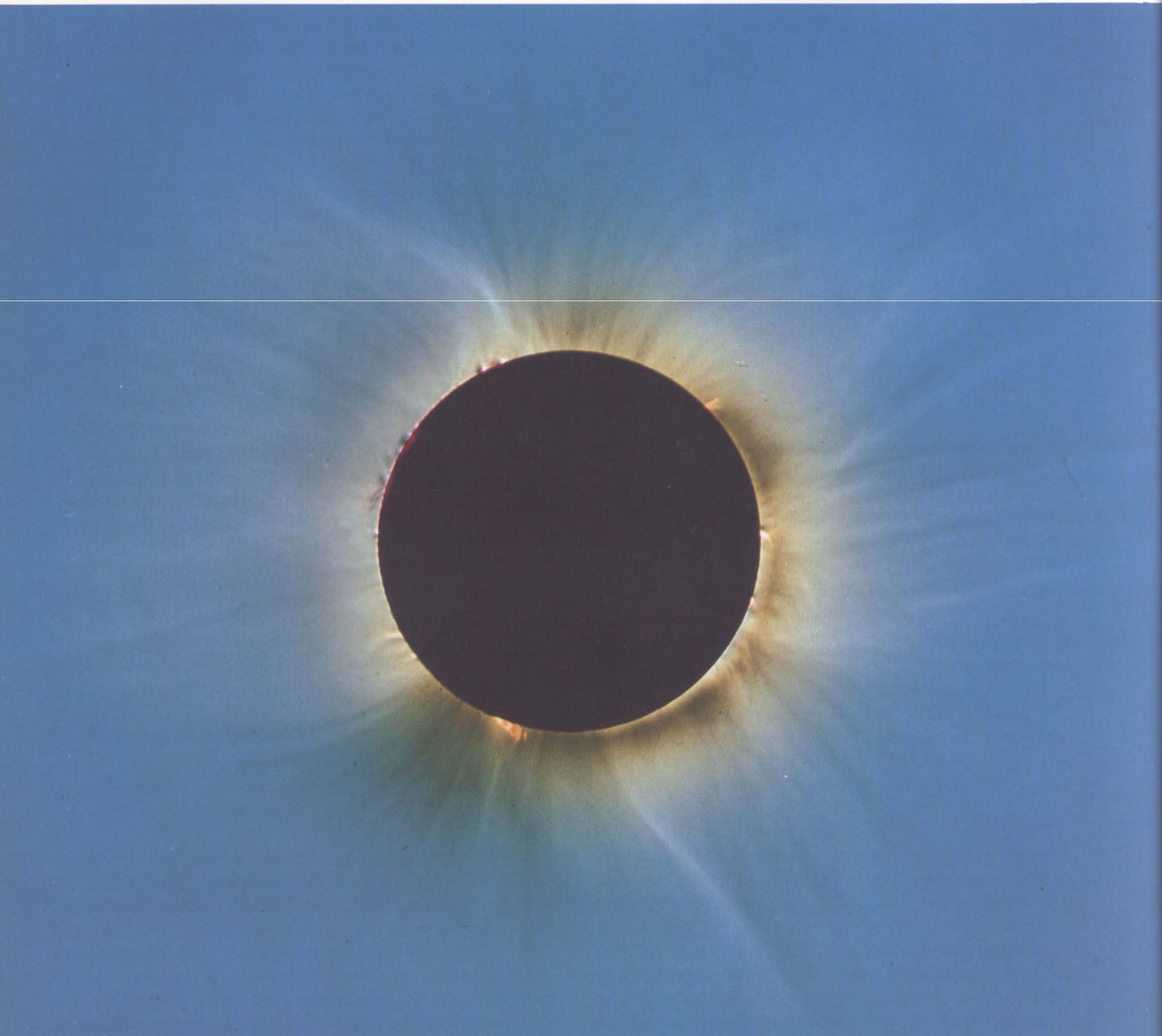
The European community involved in solar system science comprises nearly 1400 scientists.

A large and productive European community from more than 60 institutes, works on the different aspects of solar and heliospheric physics. While ESA has devoted previous missions to heliospheric physics, there has not yet been a project in solar physics. Nevertheless, there are many European solar physicists with extensive experience in space instrumentation and in the interpretation of space observations, since there has always been vigorous European participation in US solar missions.

Ground-based solar observation – a domain traditionally dominated by the large US facilities on Kitt Peak and Sacramento Peak – is gaining momentum in Europe as the German vacuum tower telescope, a 90 cm, polarisation-free French telescope, and several other advanced European solar telescopes with apertures up to 2.4 m are being installed on, or planned for, the outstanding sites on the Canary Islands.

The community involved in the area of space plasma physics has been prominent right from the outset of space research in Europe. More than 30 scientific institutes have sustained the early space ventures of ESRO and are to this day active in building space plasma instrumentation and interpreting their data. In the development and use of hardware for space exploration, these groups are at present among the most active in Europe.

With the exception of the Giotto mission, ESA has not yet pursued the exploration of bodies in the solar system other than Earth. Scientists of the ESA community have, however, already participated as individuals in planetary missions of both NASA and the Soviet Union. An ESA programme in planetary exploration could serve a large European planetary science community: more than 450 scientists with interests and capabilities in planetary research have been identified in a survey of the European Science Foundation (ESF).



The corona photographed in white light during the Total eclipse of July 31 1981, using a radial neutral filter. This picture shows very well how the structure of the corona is governed by magnetic fields. Clearly visible are the so-called helmet streamers, shaped by the magnetic field and the expanding solar wind (Institut d'Astrophysique - CNRS, Paris; courtesy S. Koutchmy)

3. Report of ESA's Topical Team on Solar and Heliospheric Physics

J. Christensen-Dalsgaard
Ph. Delache (Chairman until 20-02-1984)
P. Hoyng (Chairman from 20-02-1984)
E.R. Priest
R. Schwenn
J.O. Stenflo

Solar and heliospheric physics is one of the liveliest and most highly developed branches of astrophysics at the present time. Key areas include global oscillations, the magnetic structuring of the atmosphere, coronal heating and the acceleration of the solar wind. Much of the observed structure represents the result of subtle nonlinear interactions between a magnetic field and a plasma, and an understanding of both the small-scale microscopic processes and the larger-scale magneto-hydrodynamics is essential.

The study of the Sun, our nearest star, and its sphere of influence is of central importance not only for astronomy as a whole, but also for such basic areas as magneto-hydrodynamics, plasma physics, atomic physics, particle physics, and General Relativity. Despite the fact that our understanding has progressed significantly over the last decade, our knowledge remains deficient in many crucial respects.

3.1 Solar and heliospheric physics: an overview

3.1.1 The interior of the Sun

The Sun plays a central role in calibrating and testing the theory of stellar structure and evolution, which forms a cornerstone of astrophysics. In recent years, a new and powerful diagnostic tool, helio-seismology, has become available, whereby observed frequencies of solar oscillations are used to study the solar interior. So far about 1000 individual frequences have been measured with an accuracy better than 0.1%. These data provide stringent constraints, which current models do not completely meet. Small, but highly significant frequency differences remain, the analysis of which has only just begun. In future, application of inversion techniques is expected to yield, from the observed oscillation frequencies, a detailed model of the Sun's internal structure, including the variation of the speed of sound, and the speed of rotation with radial distance from the centre.

The mean static structure of the Sun as deduced from helio-seismology should allow clarification of many uncertainties:

i. *Helium abundance*
The observed oscillation frequencies should enable an accurate determination of the solar helium abundance. This would have important implications for cosmology.

ii. Internal mixing
It should be possible to measure the effects of partial mixing near the centre of the Sun. Such mixing would affect the age determinations for stars, and ultimately perhaps estimates of the age of the Universe.

iii. *Neutrinos*
The measured flux of neutrinos originating from nuclear reactions in the solar core is substantially below the theoretical predictions. Possible explanations include an inadequate solar model or an oscillation between different neutrino states. Combining a firm prediction of the solar neutrino flux with the observed flux could determine the mass difference between neutrino states. This might be the only way to detect it, if this mass difference is very small.

iv. *Detailed solar structure*
Effects of convective overshoot at the base of the convection zone, and of large-scale magnetic fields may be detectable.

v. *Physics of matter*
The data may permit testing of the theories of the thermodynamic state of matter under conditions that are difficult or impossible to obtain in the laboratory. Of particular interest are the equations of state and the opacity.

vi. *Mean rotation*
Knowing this accurately will permit the testing of dynamo theories and of models of the convection zone. In addition, the gravitational quadrupole moment could be calculated, which is important for tests of General Relativity.

The dynamic state of the solar interior is known with even less certainty than the stationary state. In particular, the structure of the convection zone extending over 14 pressure scale heights and its interaction with magnetic fields remains one of the greatest enigmas in solar physics. Statistical theories of dynamo action explain the broad features of the solar cycle, but many questions are unsolved. Theory and large-scale numerical modelling of the convection zone will remain important in the future, as will long-term, synoptic observations:

vii. *Solar cycle*
Measurements of variations of the solar radius, luminosity, oscillation frequencies, differential rotation and surface magnetic fields may point to the location of the source of the solar magnetic field and reveal properties of the dynamo mechanism(s).

viii. *Giant convection cells*
Frequency shifts and their time variation should provide information on the properties of large-scale convective velocity fields.

3.1.2 The atmosphere of the Sun

The origin of all activity in the solar atmosphere is seated in the outer convective layer where magnetic field is continuously generated and removed by buoyancy through the photosphere into the chromosphere and corona. At the same time, convective motions twist and stretch the field, adding energy to it. The magnetic field disposes of this energy in a variety of ways in the solar atmosphere, producing the hot corona, mass motions, surges and solar flares.

A major advance of the last decade is the realisation that the magnetic field, in the photosphere, chromosphere and corona, is highly inhomogeneous and that it dominates many of the plasma structures that we see. Several topics are of particular importance for future study:

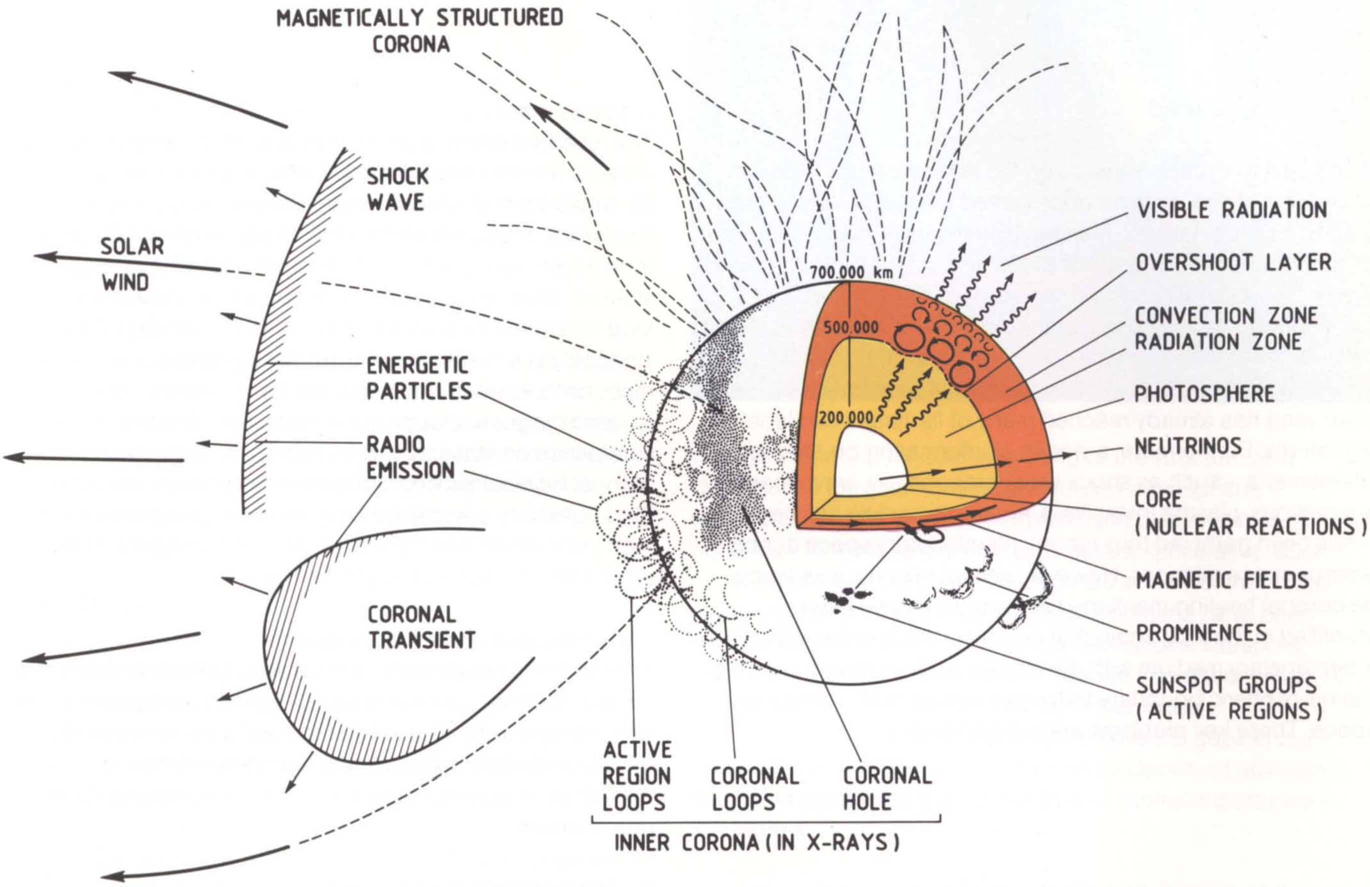
i. *Photospheric magnetic fields*
Magnetic flux in the photosphere is organised in a hierarchy of discrete elements, called flux tubes, in which the field strength is roughly constant while the magnetic flux varies by a factor of 10^5 between tiny filigree elements and large sunspots. This discovery laid a new foundation for the understanding of the role of magnetic fields in the dynamics and energy balance of the solar atmosphere. Theoretical work and high-spatial-resolution observations in the ultraviolet and visible are needed to understand the details of formation, dynamics and evolution of these flux tubes as well as the associated downflows and spicular motions.

ii. *Coronal heating*
It is now realised that, apart from possibly the low chromosphere, acoustic waves are not responsible for heating the outer atmosphere, but probably some type of magnetic mechanism, as yet unidentified, is operating instead. Intensive theoretical work is in progress and high-resolution coronal observations are urgently required to solve this long-standing problem. Possible mechanisms include magnetic waves, whose dissipation is greatly enhanced by phase mixing and resonant absorption, and impulsive reconnection at small current sheets generated by topological dissipation or tearing-mode turbulence.

iii. *Magnetic coronal structure*
The corona consists of open magnetic regions, called 'coronal holes', whose detailed physical characteristics are as yet unknown, and closed magnetic regions. The latter show up as a highly intertwined collection of hot loops, whose thermal and magnetic structure and stability are a very active area of research. The spatial and spectral resolution of existing observations is insufficient to provide the basic properties of such structures. Many basic features of prominences are also not understood: their overall magnetic structure, their fine-scale thread-like thermal structure, their complex velocity patterns, their long-term stability and their formation, evolution and disappearance.

iv. *Solar flares*
Eruptive magnetic instability can cause prominence eruptions and large flares, both of which produce coronal transients. The flare energy release is by magnetic reconnection, which converts stored magnetic energy into kinetic energy, heat and fast particle energy. However, the details of the instability and energy-release process remain to be worked out, and observed adequately, and the mechanism for accelerating enormous numbers of particles to high energies is still unknown. Indeed, the previously accepted theory for particle acceleration has been proved false by recent hard X-ray and gamma-ray observations from the Solar Maximum Mission (SMM) satellite.

Composite drawing showing the most important solar and heliospheric phenomena. Note that these are not necessarily all present at the same time. Likewise, some are only visible in X-rays or radio waves, others only in 'visible' light.



All solar energy derives from nuclear reactions in the extremely hot core; in the centre the temperature is of the order of sixteen million degrees. The energy is transmitted first through radiation and then, in the outer 200,000 km, by convection. Eventually, it escapes into space as visible radiation from a relatively thin and cool layer called the photosphere (temperature about 6000 degrees). The nuclear reactions produce also neutrinos and these are able to escape directly from the core into space.

The convection zone and the overshoot layer are believed to excite small global oscillations of the Sun. The combination of non-rigid rotation and convection renders the convection zone into a giant dynamo where electric currents and magnetic fields are generated cyclically (the 22-year solar cycle). Buoyancy pushes the fields upwards, leading to the formation of active regions, that is, a group of sunspots together with the surrounding gas. The magnetic field covers the entire solar surface in an extremely inhomogeneous way.

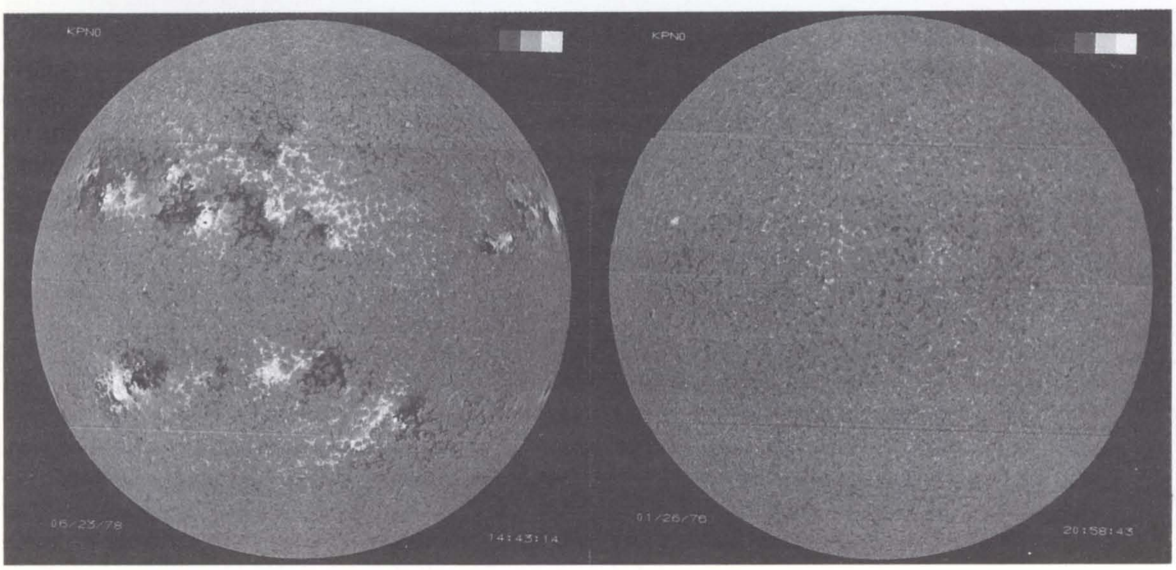
The magnetic field also shapes and heats the tenuous corona to a temperature of about one million degrees. The lower corona consists of a collection of magnetic loops locking hot gas, and open regions, named coronal holes, filled with slightly cooler gas. Prominences, however, contain very cool gas, supported and thermally insulated by the magnetic field. The corona is so hot that it expands continuously into space. This is the solar wind. Near the Earth it reaches a speed of several hundred km/sec. High-speed streams appear to emerge from coronal holes. The solar wind is partly driven, directly by the magnetic field. The heliosphere is the region around the Sun where the influence of the solar wind is noticeable. Its size and shape is neither well-known nor well represented in the figure: in the Earth's orbital plane the heliosphere is believed to extend over a distance of the order of 50 to 100 times the Sun-Earth distance.

Numerous transient effects occur in the corona. Magnetic explosions, called solar flares, generate intense local heating and copious amounts of energetic particles. Sometimes they cause a coronal transient, a giant expanding plasma cloud, and/or shock waves in the heliosphere.

3.1.3 The solar wind

In the past few years research on the solar wind has widened vastly. Space probes have approached the Sun to as close as 0.3 AU (HELIOS 1 and 2, Mariner 10), while others are about to explore the very outer regions of the heliosphere, up to 25 AU at present (Pioneer 10 and 11, Voyager 1 and 2). On the other hand, powerful orbiting coronagraphs have expanded our view of the solar corona from the solar limb up to $10\,R_\odot$ (OSO 7 and 8, Skylab, SMM, P78-1); in other words into a region where the solar wind has already reached many of its 'final' interplanetary signatures. Furthermore, a wealth of information on all kinds of phenomena – such as shock wave propagation, wave–particle interactions, plasma instabilities, energetic particle acceleration – has been gathered throughout interplanetary space during various space missions. However, several missing links (such as coronal heating mentioned in para. 3.1.2 have been identified in the long chain that connects the Sun through the interplanetary medium with the planets and eventually reaches the heliospheric boundary that separates us from interstellar space. These key problems are outlined below.

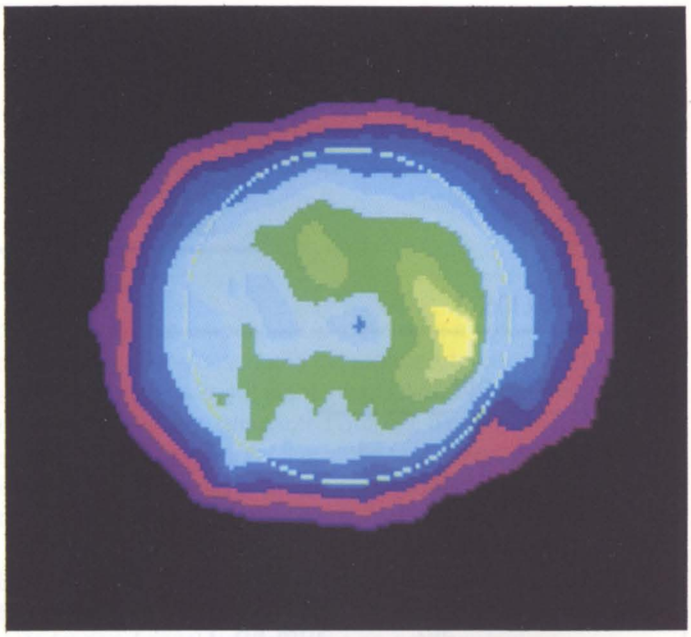
Solar surface magnetic fields. Black and white represent opposing polarities. The picture to the left is taken during solar maximum. The field is extremely inhomogeneous. Visible are sunspots and 'plages', grouped together in two belts, and a 'network' covering the entire Sun. The cellular pattern is caused by the underlying convective motions. The smallest magnetic element is believed to be about 150 km in diameter, that is, one tenthousandth of a solar diameter. The picture to the right is taken during solar minimum. The activity belts have disappeared, but the network is still there (National Solar Observatory, Tucson, Arizona; courtesy W.C. Livingston)



i. *Acceleration*
The mechanisms for accelerating both high- and low-speed streams are still not understood. High-speed streams can often be traced back to coronal holes. Recent measurements and theoretical work indicate that the energy and momentum fluxes from Alfvén waves are insufficient to heat and accelerate the streams. Slow streams appear to come from closed magnetic loop structures, but the way they do so is unknown. One possibility is a non-stationary emission process due to magnetic reconnection, which may account for the recent observation of isolated magnetic clouds in the solar wind. Another is emergence on stationary open field lines, either rooted in coronal holes or leaking out from mainly closed structures. A third possibility is acceleration in the form of numerous thin high-velocity jets that have been revealed by recent high resolution UV observations of the Sun.

ii. *Composition and charge states*
The chemical composition and charge states of different ions remain 'frozen-in' once the plasma has left the corona. Solar-wind observations should therefore allow the temperature, density and velocity close to the Sun to be inferred, as well as the nature of plasma ejected during solar flares and eruptive prominences.

iii. *Three-dimensional structure*
The Sun appears at large distances to be a rigidly rotating, tilted magnetic dipole, with the magnetic sector boundary between inward and outward pointing field lines resembling the wavy skirt of a spinning ballerina. This structure evolves in a complex manner with the solar cycle and may somehow modulate the galactic cosmic rays. An alternative cause of the modulation might be the formation of giant expanding 'shells'



A radio synthesis map of the Sun at metric wavelength obtained with the Nançay Radioheliograph on 1st July 1980. (Observatory of Paris - Meudon; courtesy P. Lantos)

produced by series of large flares. Sampling the solar wind out of the ecliptic plane should soon be possible with the ISPM spacecraft, but simultaneous observations from other spacecraft would be invaluable in order to separate temporal and spatial effects and to determine the three-dimensional shape of solar-wind structures.

iv. *Coronal transients*
The connection between coronal transients and interplanetary shock waves is now being studied. Important questions include the shape of transients, the mechanism for accelerating them, the relation to erupting prominences and flares, the association with solar radio bursts, and the reconnection that must take place to prevent a build-up of magnetic flux in the interplanetary medium.

v. *Energetic particles*
A series of unresolved questions concerns the generation and acceleration of energetic particles in the course of solar flares, and their propagation through interplanetary space. Also, the problem of acceleration of particles at interplanetary shocks has recently become a subject of intense research, both theoretical and experimental.

Solar-wind physics expects in future to close the gap between solar physics and interplanetary physics, i.e. between solar optical observations now reaching out to 10 $R_\odot$ and in-situ measurements going in not closer than 60 $R_\odot$. In particular, measurements of flow fields and magnetic topology from the transition region through the corona as far out as possible are highly desirable. Powerful new instruments such as EUV spectrometers with very high spatial and spectral resolution, combined with EUV and X-ray imaging telescopes and white-light coronographs are required. On the other hand, it is also important to approach the Sun as close as possible and perform measurements even inside the Alfvénic point where the solar wind is accelerated. Observations of radial gradients between 0.3 AU and 1 AU have already revealed that the profiles cannot simply be extrapolated back to coronal conditions. Unknown mechanisms regulating the ion temperatures, ion velocities and distribution functions are waiting to be uncovered in the unexplored space between the corona and 0.3 AU.

3.1.4 Summary

The Sun and the heliosphere provide us with a unique giant laboratory, where the interaction of magnetic fields, velocity fields and plasma-physical processes can be well observed because of their relative proximity and brightness. It is vital for astronomy as a science to exploit these factors fully, because similar magneto-hydrodynamic and microscopic plasma processes play a crucial role in many other astronomical objects. Without a full understanding of the structure and dynamics of the solar interior and (outer) atmosphere, extrapolation of its thermal, magnetic and plasma-physical behaviour to these objects remains at best speculative. Such an extrapolation is urgently needed now in view of the 'solar-stellar connection', since solar-type phenomena have been discovered on other stars, including oscillations, starspots, stellar flares, stellar cycles, stellar coronae and stellar winds. A great challenge lies ahead of us, both theoretical, technological and observational, to remove the gaps in our knowledge as expounded above. The availability of advanced, dedicated spacecraft missions will be of central importance in this regard.

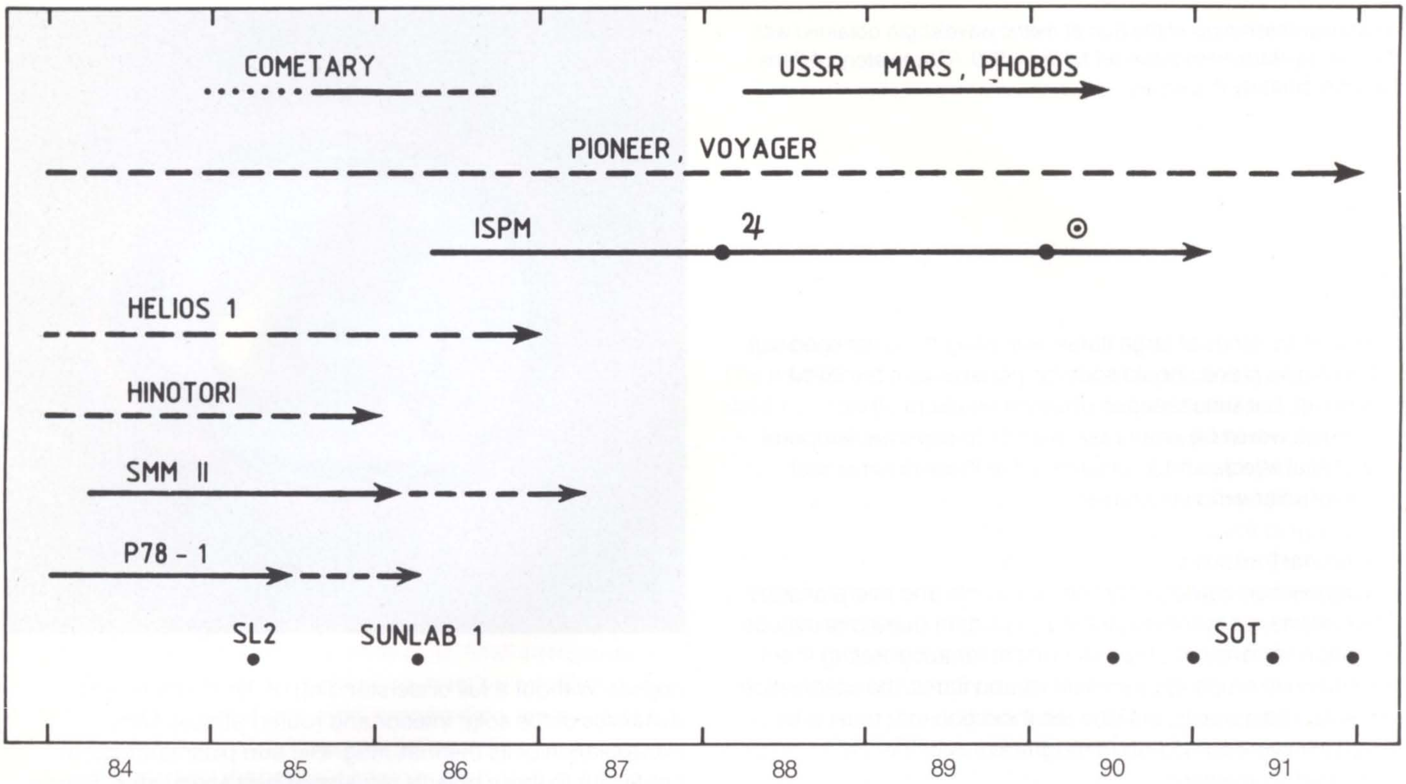
3.2 Solar and heliospheric physics in Europe

It is remarkable how the European solar-physics community has played a leading role in so many areas, in spite of their ground-based facilities being largely inferior to those in the US, and although no solar physics mission has yet been carried out by ESA. Europe is strong in practically all areas of relevance to solar and heliospheric physics. The solar and heliospheric community in countries affiliated to ESA totals about 600, and the geographical distribution of the expertise is wide. Europeans have made major contributions to a series of international programmes, in particular OSO 8, SMM, HELIOS, and ISEE-3. A major ESA project in this field would therefore be of great importance to a large number of European countries.

3.2.1 The scientific community in Europe and its expertise

We will limit ourselves to mentioning examples where European scientists have led development and have a particularly strong standing:

i *Solar interior*
- discovery of global nature of solar oscillations
- observation of low-degree p-mode oscillations
- theoretical interpretation of solar oscillations
- development of dynamo theory for the origin of cosmic magnetic fields



Available and approved missions for solar and heliospheric physics. Uncertain project status, limited time coverage, etc., are indicated by a broken line.

- application of dynamo theory to the solar cycle
- diagnosis of the solar dynamo by analysing differential rotation and magnetic field patterns.

ii. *Solar atmosphere*
- discovery that photospheric magnetic flux is in the form of isolated kilogauss flux tubes
- theoretical models of flux-tube concentration and of flux-tube wave modes
- observational studies of waves in photosphere and chromosphere
- space observations and interpretation of chromosphere and transition region
- development of atomic physics for spectroscopic diagnostics
- theory of acoustic heating of the lower chromosphere
- theory of magnetic mechanisms for heating the solar corona
- theory of magnetic-loop structures
- observations and theory for formation, structure and stability of prominences
- observations and theory of solar radio emissions
- flare studies with instruments on the Solar Maximum Mission
- theory for magnetic instability and energy release by reconnection in solar flares.

iii. *Heliospheric physics*
- determination of three-dimensional proton velocity distribution
- discovery of unknown nonthermal 100–300 eV electron beam carrying the total electron heat flux of the solar wind
- estalblishment of the existence of sharp boundaries between slow and fast plasma streams in close correspondence with coronal holes
- establishment of unambiguous correlations between coronal transients and their interplanetary responses (shocks, turbulence, etc.)
- quantitative results on solar-cycle modulations of the solar wind
- establishment of anomalies in the relative C, N, O cosmic-ray abundances in certain energy regions
- enhancement of ^{3}He after some solar flares and the occurrence of high He$^+$ fluxes after others
- determination of collisionless shock structures and shock particle acceleration.

3.2.2 Available and planned instruments/experiments

The major *space missions* relevant to solar and heliospheric physics are shown in the chart above. The solar atmosphere and corona is studied with P78-1 and in particular by the Solar Maximum Mission II (coronagraphs, UV-, X-ray-imaging, γ-rays), and by the Japanese Hinotori satellite. There is extensive European involvement in the SMM (hardware, guest-investigator programme).

Several European groups are making use of Spacelab for solar physics:

A coronal helium-abundance experiment is being built in the UK (Rutherford/Mullard) for SL2. The three American experiments include a package for measuring velocity and magnetic fields, a UV spectral irradiance monitor (with

European participation) and a high-resolution UV telescope and spectrograph.

Sunlab I (with four solar instruments) has been approved for the nineties. The Solar Optical Telescope will be very important. The scientific objectives of SL2, Sunlab and SOT were highly regarded by the Team. It is hoped that these NASA missions, including the Pinhole Occulter Facility (the X-ray counterpart of the SOT currently under study) will develop into a continuous programme.

For heliospheric physics, important data will be collected by the International Solar Polar Mission (now named 'Ulysses'), although the quality of the data will suffer from the cancellation of the second (US) ISPM spacecraft.

The HELIOS 1 spacecraft is still functioning (50% of the time) and operations may be extended to the end of its functional life. This mission might therefore provide some of the required reference measurements for ISPM and Giotto.

There are five cometary missions (Giotto, ISEE-3, one Japanese and two Russian). These will provide largely traditional in-situ solar-wind measurements during the cruise phases of the orbits. The same is true for the USSR mission to Mars and Phobos (launch 1988). Pioneer and Voyager, finally, contain a whole set of particle and fields instruments, and are expected to deliver data on the outer heliosphere for at least a decade.

Much of the development of *ground-based facilities* for solar physics is taking place on the Canary Islands. Germany is setting up two major facilities at the Teide Observatory on Tenerife to be operational in 1986: (i) A new 60 cm Vacuum Tower Telescope (VTT) equipped with spectrographs, filters, and a magnetograph. (ii) The 45 cm Göttingen Gregory-Coudé telescope at Locarno, Switzerland, is being moved to Tenerife.

France is building a 90 cm evacuated, polarisation-free telescope, THEMIS, to become operational at the Teide Observatory, Tenerife, by the end of the 1980s. Its prime objective is the investigation of solar magnetic fields.

The Swedish Capri Observatory was moved a few years ago to La Palma in the Canary Islands. The Netherlands plan to set up an experimental 45 cm telescope on La Palma.

Among the other ground-based observing facilities in western Europe, the main centres are at Meudon (Paris), Pic du Midi, Arcetri (Florence), and Oslo, but a number of smaller and more specialised instruments are available to several other groups (e.g. in Switzerland and Austria). Dedicated instruments for observation of solar radio emissions are available in Bordeaux, Nancay, Bern, Zürich, Trieste and Weissenau.

Groups in France and the UK plan to form a network of observing stations distributed in longitude, to observe global solar oscillations without night interruption. Various national balloon experiments are carried out, e.g. measurement of the solar constant or the solar flux in the far-IR (Switzerland). There is a French plan to record solar oscillations from a tethered balloon above the South Pole.

By far the most ambitious project for the future is the Large European Solar Telescope (LEST), a 2.4 m aperture polarisation-free telescope based on next-generation technology. Adaptive optics are foreseen to correct wavefront errors in real time, enabling diffraction-limited performance. A Phase-A report for LEST was completed in 1982, mainly by scientists from Norway and Sweden, and in 1983 the LEST Foundation was created. The likely site for LEST is on the Canary Islands. The financing of the construction phase has, however, not been resolved.

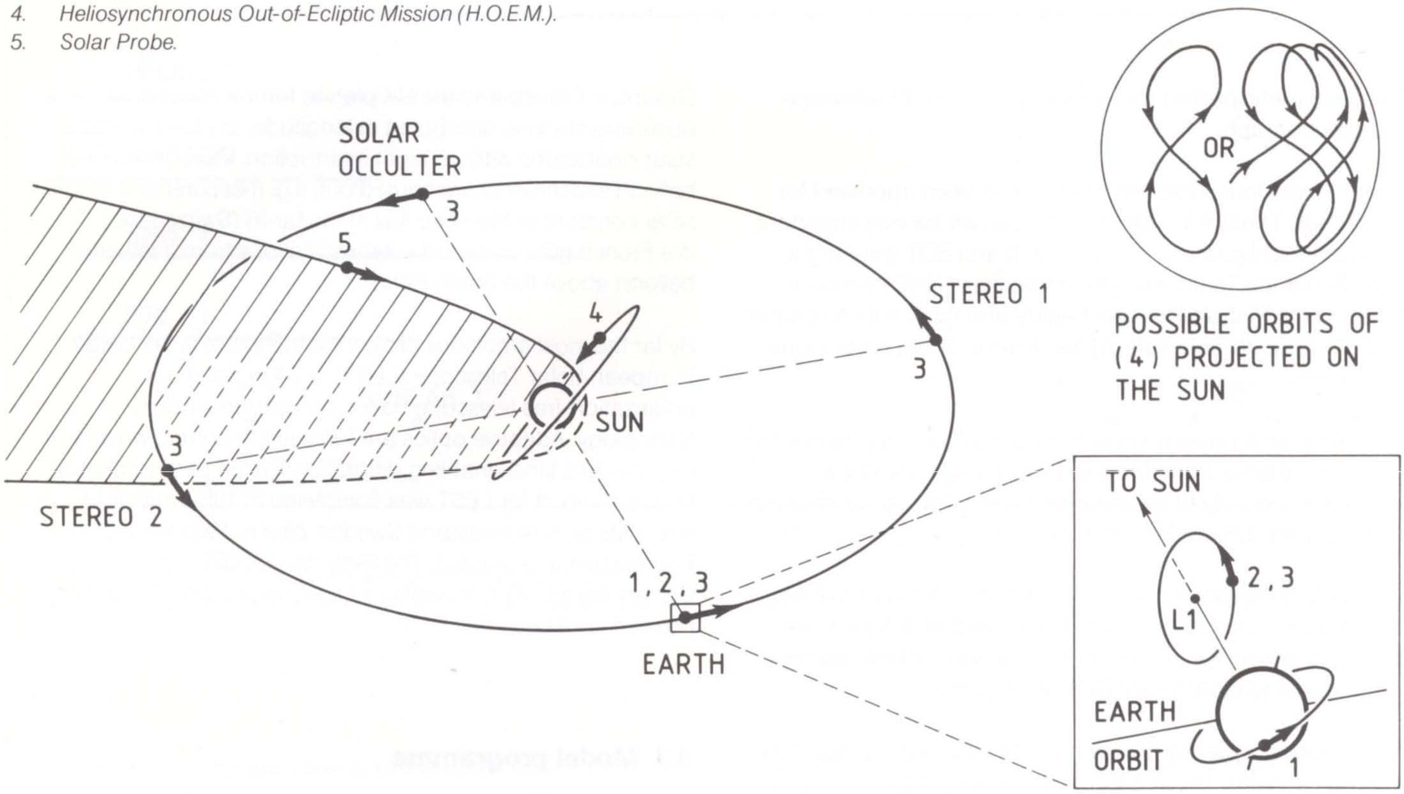
3.3 Model programme

The various approved missions in solar and heliospheric physics were listed in para 3.2 and in the chart, page 00. When comparing these missions with the outstanding science reviewed in para 3.1, we find that most of the scientific needs will not be adequately satisfied. In particular the following fundamentally important science will not be addressed at all:

- Helio-seismology
- Measurement of coronal magnetic fields
- Coronal imaging beyond 10 $R_{\odot}$
- Concerted solar and heliospheric observations
- Advanced plasma physics
- Stereoscopic view of solar structures
- Synoptic view of solar structures
- Synoptic view of the Sun
- In-situ measurements in the corona inside about 60 $R_{\odot}$
- Long-term observations (for any of the above topics), to investigate solar-cycle variations.

Below, we propose a general and long-range programme that would fill the above-mentioned gaps in a logical sequence and thereby achieve the scientific objectives outlined in para 3.1. We will first describe the five basic components of this programme. Next, we will indicate how they would fit together in an overall strategy, including a possible time sequence of implementation. The proposed programme incorporates the ideas submitted by the European solar-physics community in response to ESA's call for mission concepts of November 1983. This programme was unanimously adopted by the Topical Team.

Sketch (not to scale) of a model programme for solar and heliospheric physics, consisting of five components:
1. *Free-flyers in Earth orbit.*
2. *An observatory orbiting the Lagrangian point L1.*
3. *Synoptic Array Programme (S.A.P.). This programme can be realised by complementing programme component (2) with three spacecraft in the ecliptic plane at 1 AU at position angles 90°, 180° and 270°.*
4. *Heliosynchronous Out-of-Ecliptic Mission (H.O.E.M.).*
5. *Solar Probe.*



Component 1: Free-flyer in Earth orbit
Advantages:
- Suitable for ultrahigh spatial resolution (subarcsec).
- Suitable for concerted imaging and spectrometry simultaneously in many wavelength bands (cf. Skylab, SMM).
- Retrievable if in low orbit.

Disadvantages if the orbit is low:
- Night interruption.
- No helio-seismology or heliospheric-physics possible.
- Data-acquisition problems.
- Possible interference with the radiation belts.

A geostationary orbit would be preferable from the point of view of data transmission and Earth shadowing. Such an orbit is easily accessible with Ariane. A drawback is, however, that the spacecraft would not be retrievable. A free-flyer is preferable to a manned observatory, for cost and contamination reasons.

Component 2: Lagrangian point L1 Observatory
Advantages:
- Ideal for helio-seismology.
- Continuous in-situ measurements of the solar wind.
- Continuous coronal diagnostics possible.

Disadvantages:
- The larger distance from the Earth might place constraints on data acquisition and spacecraft mass.

Component 3: Synoptic Array Programme
This component consists of an array of four spacecraft in solar orbits in the ecliptic and 1 AU, distributed at position angles 0° (L1 Observatory), 90° (Stereo 1), 180° (Solar Occulter), and 270° (Stereo 2) around the Sun. The L1 Observatory is identical to Component 2 described above. As viewed from the Earth, the Solar Occulter will circle the Sun at a projected distance of about $5 R_{\odot}$ which will allow systematic radio sounding of the solar corona.

Advantages:
- Synoptic coverage, needed for
  a. global magnetic-field modelling
  b. investigating the evolution of global structures, such as high-degree modes of oscillation, coronal holes, giant cells, magnetic patterns
  c. establishing the correspondence between solar structures and events at 1 AU.
- Stereo view of coronal structures, vector magnetic fields, directivity of particle and X-ray flares, etc.
- Probing the corona with radio-sounding techniques (Solar Occulter).

Component 4: Heliosynchronous Out-of-Ecliptic Mission
A satellite at a solar distance of about 30 $R_\odot$ has an orbital period of about 27 days, the rotation period of the Sun. Instead of strictly heliosynchronous orbits, we propose to use orbits with a substantial inclination, e.g. 50°, to the solar equator. Elliptical orbits ranging between say 20 and 60 $R_\odot$ are also conceivable. They are thus quasi-synchronous in a first approximation, but sample a large range in latitude. Versions with one or a combination of several spacecraft are foreseen.

Advantages in the case of a single spacecraft:
- Quasi-synchronous orbit, for detailed study of the evolution of solar structures and the solar wind from a vantage point close to the Sun.
- Out-of-ecliptic in-situ sampling of a wide range of latitudes within a relatively short period of time.
- Frequent good views of the polar regions of the Sun.
- Stereoscopic view
  a. in combination with Earth-based observations (e.g. the L1 Observatory);
  b. for structures with a lifetime of longer than one week, through the motion of the spacecraft.

Additional advantages with more spacecraft:
- Separation of spatial and temporal variations of structures in the inner heliosphere.
- Directivity of emissions.
- Detailed stereoscopic viewing.
- Improved synoptic coverage.

Component 5: Solar Probe
The solar probe would have a perihelion distance of a few solar radii in an orbit that may be out-of-ecliptic. The feasibility of such a mission has been demonstrated in a previous ESA mission-definition study.
Advantages:
- In-situ measurements in the solar corona down to the region where much of the solar-wind acceleration takes place.
- Determination of the solar gravity field (J_2) and testing of General Relativity (higher-order terms in the post-Newtonian theory). The information is contained in the orbit tracking data, but mixed with the effect of g-mode oscillations. The latter should be determined by the L1 observations to make disentanglement possible.

With these programme components, the scientific objectives reviewed in para. 3.1 may be achieved without any of the science gaps listed at the beginning of para. 3.3. Programme Component 1 is now partially covered by the approved NASA projects SMM II, Spacelab-2, Sunlab and SOT. However, later Sunlab or Eureca flights could usefully incorporate instruments to study, for example, coronal heating, coronal structures and coronal magnetic fields.

With regard to the time sequence of implementation of the other Components, the logical first step would be realisation of the L1 Observatory. To observe solar-cycle effects properly, it is important that an L1 Observatory be operative for a period at least comparable with the length of the solar cycle. By adding other spacecraft, the L1 Observatory can be extended into the Synoptic Array Programme. Components 4 and 5 are next-generation missions which could be realised in the late 1990s. The entire programme should be carried out in the form of a world-wide collaboration. As an example, the four spacecraft of the Synoptic Array Programme could be supplied by ESA, NASA, the USSR and/or Japan or other national programmes.

All missions contain imaging instruments. However, the cost of the above programme need not necessarily be very high. The L1 Observatory will be a Class-II mission, but in the case of a US collaboration it could become a Class-I mission. The Synoptic Array Programme could be realised without any additional cost to ESA in the framework of an international collaboration. Preliminary studies are required in order to be able to make cost estimates for Components 4 and 5.

3.4 Recommendations

The following recommendations were formulated by the Team:

i. A vigorous solar and heliospheric research programme, commensurate with the capability, vitality and needs of the corresponding European community, should be given strong support.

ii. The strategy for achieving the solar and heliospheric science objectives outlined in para 3.3 is strongly recommended. In particular this would mean:
- The SOHO mission should be realised as a comprehensive, multidisciplinary solar-heliospheric observatory. This would provide a major support for the International Solar Terrestrial Physics Programme.
- Efforts should be undertaken to find partners (including the USSR) who could provide components of the Synoptic Array Programme as a world-wide venture. The SOHO mission could be a basic building block of this programme.
- Feasibility studies for the Helio-synchronous Out-of-Ecliptic and Solar-Probe missions should be initiated.

iii. The use of unmanned space vehicles is to be preferred in view of the high cost and contamination involved with a manned Space Station. Should the latter be realised *and* be available to the Scientific Programme without additional cost for operations and usage, then it could be employed for those solar missions for which a low orbit is acceptable. Accordingly, Eureca, if demonstrated to be cost-effective, could be used for similar goals.

iv. The suggestion that the efficiency of the design and development process for space missions be carefully reviewed in terms of cost and management is endorsed.

v. Steps to improve data-acquisiton capabilities should be taken, since many future missions require data rates far in excess of what can presently be handled.

vi. The development of advanced propulsion and power systems should be studied in preparation for the sophisticated missions foreseen for the 1990s.

vii. A guest-investigator and data-release policy should be assessed, in particular for Principal-Investigator-type missions.

viii. A much-extended Fellowship Programme should be supported,
- to render it possible for young scientists to work in space science
- to allow senior scientists to engage more fully in space research by relieving them from teaching duties
- to ensure optimum use of data obtained and to unite European scientists by exchange.

ix. Support and coordination is needed for the setting up of a European computer network, to promote
- direct exchange of data
- exchange of software to facilitate unified data reduction and analysis
- international collaboration between groups through efficient communication
- links to the largest computing centres to facilitate large-scale numerical simulations.

4. Report of ESA's Topical Team on Space Plasma Physics

Members: M. Dobrowolny
L. Eliasson
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G. Haerendel (chairman)
A. Johnstone
S. McKenna
G. Morfill
V. Vasyliunas

The exploration of the solar system over the last 25 years has shown that space is filled with dynamic and energetic plasma. As spacecraft have probed further from the Earth's surface into interplanetary space and to five of the major planets, their instruments have revealed a previously unimagined complexity in the interplay of electromagnetic fields and charged particles. In reviewing this progress, one is struck by two observations. The first is that although the ideas of Chapman, Alfvén, Parker, Dungey and other pioneers in this field were successful in describing the basic features, the in-situ measurements have always presented major surprises in each newly explored region. The second observation is that, in spite of the diversity of the plasma environments in the solar system the same plasma processes are often found to play a dominant role.

Although there is need for further exploration, with exciting prospects ahead, the maturity of the research enables us to proceed beyond a regional, phenomenological approach to a quantitative study of important plasma processes in their respective environments.

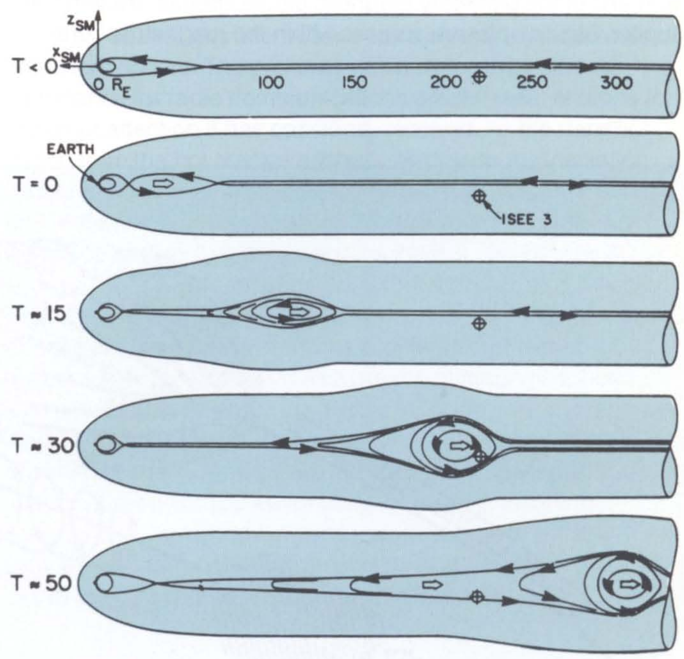
The review of achievements and outstanding problems presented at the beginning of our report is therefore organised according to plasma-physical disciplines rather than regions. Since completeness is far beyond the scope of this report, we have concentrated on some significant and exciting areas where we feel there is an opportunity for a European initiative.

The Aurora-visible proof of space plasma activity

4.1 Achievements and Unresolved Problems

4.1.1 Macrostructures

Global structures found in the plasmas of the solar system on a variety of scales are to a large extent shaped by basic plasma processes, acting singly or in combination: flow dynamics, magnetohydrodynamic coupling of the flow and the magnetic field, and interaction between the plasma and a neutral or a partially ionised medium (e.g. atmosphere or ionosphere). The interplay of these processes takes many forms, including the formation of magnetic boundaries and reconnection between magnetic field lines from different regions. On the largest scale we have the solar wind, the magnetic spiral pattern, the sector structure and high- and low-speed streams. The solar wind interacts with the strong magnetic fields of planets (Earth, Jupiter, Saturn, Mercury) to form magnetospheres, with boundaries where reconnection occurs as a particularly important process. Inside, the magnetosphere–ionosphere coupling governs the large-scale circulation of plasma, which leads in turn to a variety of plasma structures. In the case of planets with weak or non-existent magnetic fields of internal



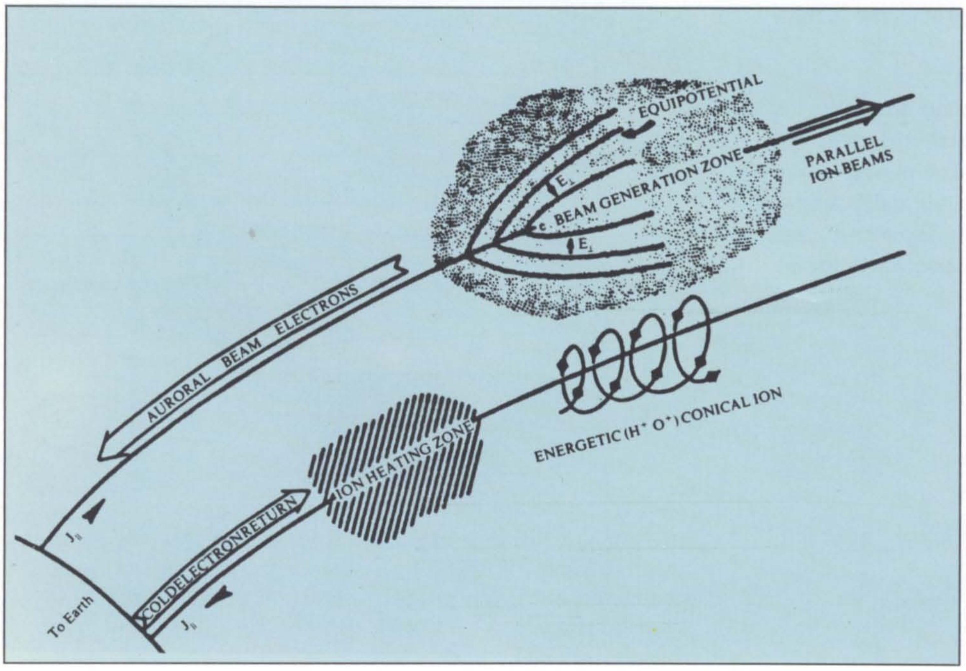
Model depicting the severance of (a longitudinal sector of) the plasma sheet at substorm onset (T=0) and its departure along the tail as a closed magnetic structure, a plasmoid. Black arrows indicate the magnetic field direction and white arrows indicate plasma flow (from Hones et al., 1984) origin (Venus, Mars), there is a direct interface between solar-wind plasma and the ionosphere, the ionopause, where the interplanetary magnetic field is being compressed and then pulled out into a tail-like structure. For all planets, the magnetosphere or the magnetosphere-like ionopause structure presents an obstacle to the solar-wind flow, resulting in the formation of a bow shock.

The terrestrial magnetosphere is not just a simple transition between the ionosphere and the solar wind. The plasma in the magnetosphere is hotter and less dense than plasma in either the ionosphere or the solar wind. It is still uncertain where and in what way energy is transferred from the solar wind into the magnetosphere; it appears that the kinetic energy of solar-wind flow is converted to magnetic energy, which in turn is dissipated to provide the heating of magnetospheric plasma, but the detailed configuration and the physics of the process (in particular the role of reconnection between magnetic field lines from the Earth and from the solar wind) are far from being fully understood.

The magnetospheres of other planets differ from that of the Earth and from each other, as a result of different external and planetary parameters and boundary conditions. These include different distances from the Sun (with consequent different intensities of solar photons and the solar wind), different strengths of the planetary magnetic dipole, greater rotation rate (Jupiter, Saturn), plasma sources within the magnetosphere from moons, gas clouds, or rings (Jupiter, Saturn), absence of an appreciable atmosphere or ionosphere (Mercury), ratio of magnetospheric to planetary radius ranging from nearly 100 (Jupiter) down to about 1.5 (Mercury). To date, no more than three to four spacecraft traversals of any of the other magnetospheres have been made, and large regions remain unexplored. To explain the great diversity of planetary magnetospheres in terms of common plasma processes acting on different scales and under different given conditions, remains a crucial test of our understanding of space plasma physics.

4.1.2 Small-Scale Structures

The exploration of space plasmas has revealed their tendency to form small-scale structures. Prominent examples are: small-scale reconnection or flux-transfer events at the Earth's magnetopause; flux-ropes generated at the Venusian ionopause and transported deep into the ionosphere; thin and often multiple auroral arcs, which again break up into moving rays or curls; isolated electric-current tubes in the magnetosphere; ionospheric irregularities of various types. Small-scale structures represent local concentrations of currents, electric fields or other quantities in thin sheets or filaments, where the thresholds for the onset of certain micro-instabilities are easily exceeded and new modes of plasma interactions can be created. The resulting anomalously high



Schematic of suggested electrodynamic structure of near-Earth magnetosphere at auroral latitudes. An electric double layer accelerates downward (towards Earth) electron and upward ion beams and a consequent $j_{=}$. The return current is assumed to be carried by upwardly drifting cold electrons whose bulk energy feeds ion-cyclotron instabilities, which in turn accelerate H^+ and O^+ in the direction transverse to B (from Ashour-Abdalla & Okuda, 1982) values of electrical resistivity, diffusivity and viscosity, combined with the small spatial scales of the macrostructure, lead to a drastic shortening of macroscopic transport time-scales, often by many orders of magnitude.

A deeper understanding of the overall dynamics of interacting cosmic plasmas will not be possible without the consideration of small-scale structures. So far, little is known about their three-dimensional morphology, their growth and decay, and the sites of anomalous microprocesses therein. This is mainly due to the lack of multiple-spacecraft missions with high time resolution in some of the key regions of the Earth's magnetosphere where these fine structures can be studied most economically. In spite of some detailed studies in the ionosphere, partly by active plasma experiments, much of our present thinking in this field amounts to no more than suspicions and speculations. Here lies one of the most prominent tasks for in-situ plasma research in the solar system.

4.1.3 Microprocesses

Microprocesses are defined as those processes occurring on the smallest spatial scales (~ ion gyro radius) and temporal scales (gyro period), where the details of the particle velocity distribution are important. We are therefore concerned with the elementary interaction of charged-particle distributions with electromagnetic fields. Many modes of wave – particle interactions are now reasonably well understood. Different aspects of the linear and quasi-linear theories of these interactions have been verified thanks to the detailed observations made onboard, for example, Geos, ISEE and Helios. Whilst the origin of most of the natural wave phenomena is known in general terms, there is still some debate about the exact mechanism by which planets are important radio transmitters (in the myriametric or kilometric range for the Earth, in the hectometric or decametric range for Jupiter). It is believed that electrostatic or electromagnetic waves energise heavy ions in planetary atmospheres, enabling them to be injected into the magnetosphere, but the process is by no means fully understood. Similarly, the exact role that electrostatic and electromagnetic turbulence plays in anomalous transport or heating processes is not clearly understood because of lack of measurements with sufficient time resolution (see fine structures).

On the other hand, our understanding of plasma processes occurring at or in the vicinity of interplanetary or magnetospheric shocks has been greatly improved. Investigations of the region upstream from the Earth's bow shock have led to substantial clarification of the complex mechanisms by which particles reflected from the shock are energised and redistributed through wave – particle interactions. Problems still remain; in particular our understanding of quasi-perpendicular shocks is much better than that of the quasi-parallel shocks. Also we do not yet understand how a suprathermal 'seed' particle population is extracted from the plasma, what the significance of energy-loss processes is (e.g. Coulomb collisions), what the behaviour of a multicomponent plasma is (protons, alpha particles), etc.

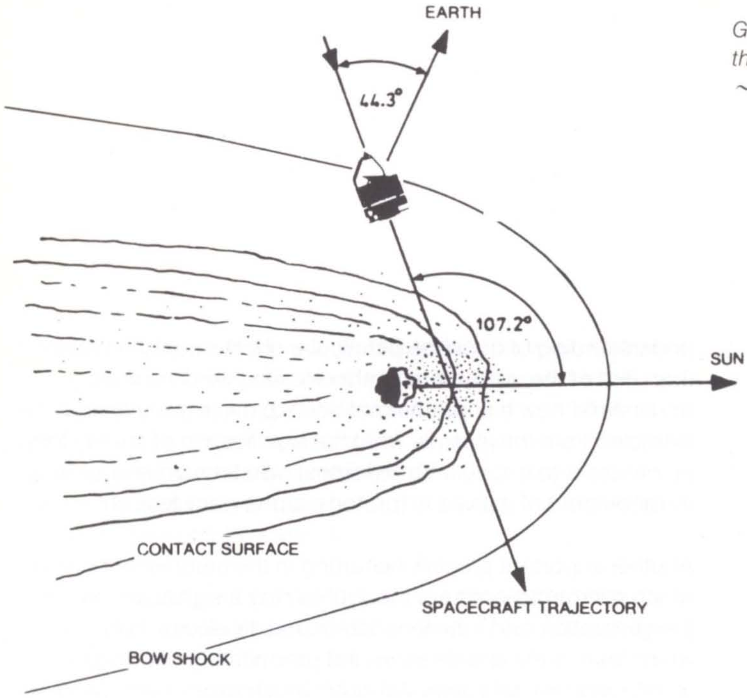
Another important process occurring in the magnetosphere, in which microprocesses are thought to play a significant part, is the generation and maintenance of parallel electric fields, which lead to the acceleration and precipitation of particles along magnetic field lines. Although much experimental and theoretical work has been put into the study of this phenomenon, little is known about the exact microprocesses which underly such quasi-static structures (e.g. electrostatic shocks, double layers, kinetic Alfvén waves).

Active experiments in the near-Earth plasma (e.g. Porcupine, Spacelab) have proved to be a powerful tool for studying fundamental plasma processes. In these experiments, controlled injection of particles and generation of waves perturb the environment. Its response to these perturbations enables us to investigate such processes as wave excitation, wave – particle interaction, beam – plasma interaction, etc.

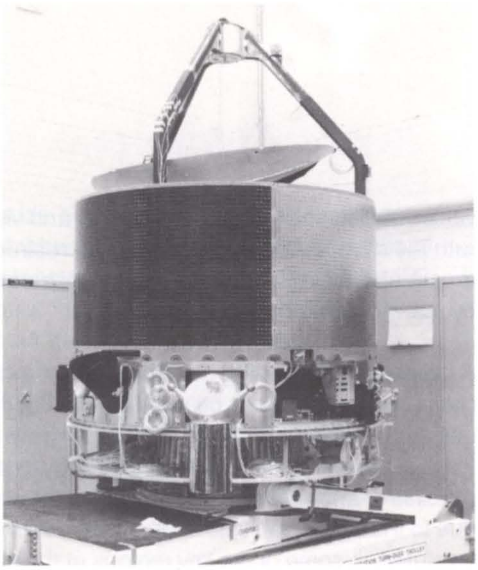
4.1.4 Plasma – Neutral Gas Interaction

Plasma – neutral gas interactions are a characteristic feature of the ionosphere. The proximity of the ionosphere and its importance for radio communications are the main reasons for the great attention it has constantly received. As the transition region from the hot magnetospheric plasma to the insulating middle and lower atmosphere, it acts as an absorber of energy, momentum and mass supplied ultimately from the solar wind via the outer layers of the magnetosphere. It also acts as an end resistor for magnetospheric current systems, as a reflector of hydromagnetic waves, as a screen on which the presence and dynamics of electron beams accelerated at higher altitudes are displayed, and as a source of magnetospheric ions. Finally, it is an easily accessible laboratory for the detailed study of plasma processes by means of remote and in-situ observations as well as by active experiments. Recently installed powerful facilities for diagnostics (e.g. incoherent scatter radar) and modifications (e.g. ionospheric heating facilities, Shuttle-borne particle accelerators) will enhance the use of the ionosphere as a natural plasma laboratory.

In the heliosphere, there are other plasma – neutral gas interaction regions where, in contrast to the ionosphere, the energy density of the plasma is not small compared to the magnetic field. The source of neutral gas may even be unmagnetised (comets or the planet Venus). Research into such plasmas has just begun and little is known about the



Geometry at Halley encounter. The spacecraft will be aimed to pass the nucleus on the sunward side. A bow shock is expected at $\sim 10^5$ km, a contact surface at $\sim 10^3$ km from the nucleus



Giotto

main processes of energy and momentum transfer from the solar wind to the cold plasma and the magnetic field, or about the role of collective ionisation processes. With the missions to comet Halley, this research will receive great attention, and undoubtedly many new questions will arise.

4.1.5 Dusty Plasmas

Atmospheres of comets, and magnetospheres of the ringed planets provide a different environment, 'dusty plasmas'. Charging and motion of individual dust particles in a plasma are well studied; collective effects of a dust population in a plasma are as yet largely unexplored. Interest in this topic has been generated by the Voyager observations of Jupiter's ring and the 'spokes' in Saturn's rings. Questions of interest include the dust as a source or sink of plasma, gravity-driven dynamo effects, transport and instabilities generated by the dust component.

4.1.6 Energetic Particles (Cosmic Rays)

The relationship of cosmic rays to space plasma physics in the solar system may be handled in two ways. One may regard cosmic rays either as an energetic component of the plasma or as individual particles reacting to, but not modifying, the dynamics of the plasma. Cosmic-ray coupling onto the plasma (transferring momentum and energy) via magneto-hydrodynamic (MHD) waves leads to a stochastic transport, which can be investigated using solar and galactic cosmic-ray observations in the heliosphere. The plasma and field morphology (e.g. streams, corotating interaction regions, neutral sheets, shocks) is very important, as is the three-dimensional structure of the interplanetary medium, which is to be investigated by the International Solar Polar Mission (now renamed 'Ulysses'). On the microscopic level, essential elements of the wave–particle interactions still need to be studied in the plasma-dominated interplanetary medium (nonlinear effects, trapping, interactions with acoustic waves, etc.). In the magnetic-field-dominated magnetospheric environment, some of these elements have been studied with considerable success.

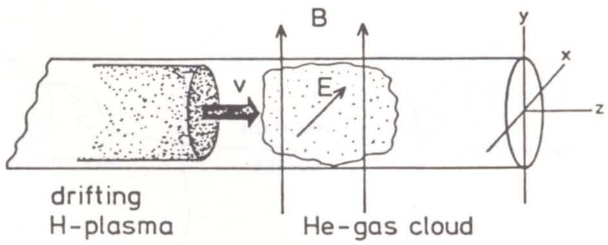
Recently, cosmic-ray acceleration by shock waves has been receiving considerable attention as a process of great astrophysical importance, capable of producing cosmic-ray energy densities comparable to that of the plasma bulk flow. An analogous process at the Earth's bow shock, producing particles of only suprathermal rather than cosmic-ray energies, has been observationally confirmed by the ISEE mission. Important further aspects remain to be studied, including in particular a predicted dynamical modification of the shock structure. Observational studies of this process and its nonlinear ramifications at the Earth's bow shock are important for cosmic-ray physics not only as a test of the basic theory, but also as a description of the suprathermal particle populations whose astrophysical counterparts provide the 'injection' needed as the input to cosmic-ray acceleration.

4.2 Relationship to Laboratory Plasma Research and Astrophysics

The links between plasma research in the laboratory, in space and in astrophysics are manifold. Cross-fertilisation between these fields has been an important element in the development of each of them. Although the parameter ranges are quite different, transfer of insights obtained in any one of these disciplines to another one is often possible and has a long history of successes.

In the laboratory, one can set up simple configurations with the

Schematic view of plasma – gas impact experiment on the critical velocity (the velocity at which the kinetic energy is equal to the ionization energy of the neutral gas) as first performed by Danielson (1970). The plasma arrives at supercritical velocities and is slowed down to the critical velocity, while the neutral gas is ionized



purpose of isolating a single phenomenon; in space one can study the free interplay of natural processes 'in situ'; in astrophysics one has to extract the information on plasma configurations and processes by means of the great spectrum of 'remote-sensing' techniques. Near-Earth space can also serve as a plasma laboratory in which the absence of walls and the long spatial and temporal scales (in comparison with laboratory plasma) facilitate certain measurements, in particular those concerning microprocesses, which are much more difficult to perform in the laboratory. Among all the astrophysical objects, the Sun has a singular position because of its proximity, which allows high-angular-resolution measurements. The links between astrophysics, in particular solar physics, laboratory plasma research and space plasma physics are therefore particularly intimate and, due to the differences in characteristic physical parameters, they are also largely complementary.

4.2.1 Laboratory and Space Plasma Physics

Laboratory plasma experiments and space plasma observations, with their respective theoretical development, have already proved mutually illuminating. On the one hand, phenomena first proposed or identified in a space context have subsequently been observed and studied in detail in the laboratory (e.g. magnetic-field reconnection, collisionless shocks, the 'critical-velocity' effect). On the other hand, phenomena first observed in the laboratory have subsequently assumed great importance in space plasma physics; a primary example is the formation of electrostatic double layers, identified in gas-discharge experiments and now a key concept in our present understanding of auroral-particle acceleration.

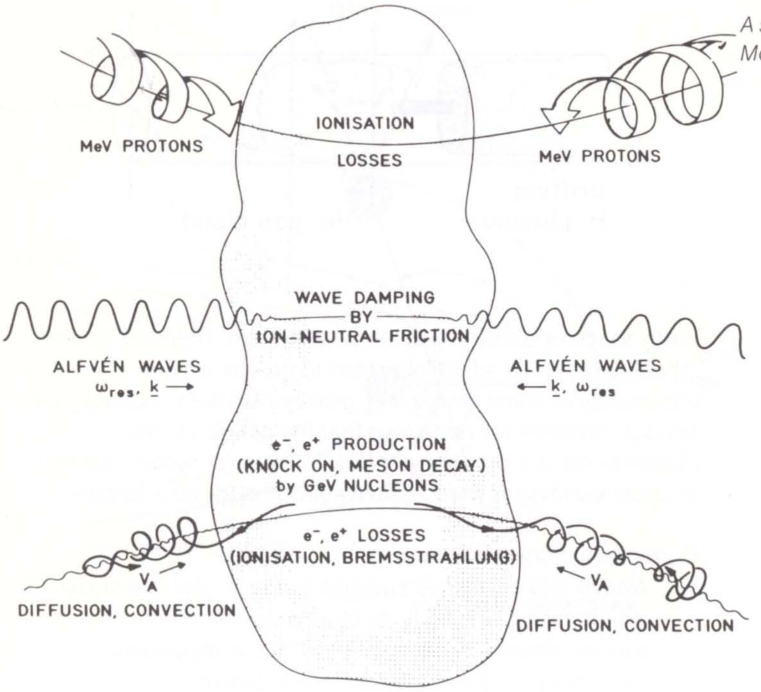
The areas where laboratory work is expected to make substantial further contributions to our understanding of space plasmas include the following: reconnection experiments for different plasma parameter ranges (relevant to solar flares and coronal processes, interactions at the magnetospheric boundary and the magnetotail, as well as in many astrophysical contexts); beam – plasma interactions and high-amplitude waves in plasmas (relevant to many active experiments in the magnetosphere and the ionosphere); physical processes near highly charged probes (relevant to spacecraft charging, tethered satellite investigations); stability and fine structure of plasma and magnetic-field boundaries, anomalous transport processes, plasma turbulence, global flows, etc.

4.2.2 Astrophysics

There are many plasma-physical processes important in various areas of astrophysics which have analogues in near-Earth space or elsewhere in the solar system. There will be a difference of scale, which may lead to greater relative importance of some effects (e.g. gravity, radiation, relativity), but enough similarity will remain so that the detailed in-situ observations of a process, possible in the solar system, will help in understanding its inaccessible astrophysical counterpart.

Examples include the following:

1. Weakly ionised diffuse plasmas found in cool interstellar clouds, which are the birth-sites of stars and planets and play an important role in galactic structure and evolution, have many similarities to plasmas in planetary ionospheres. Important physical processes are, for example, ambipolar diffusion, magnetic braking, wave damping by ion-neutral friction, anomalous heat conduction and ionisation effects.
2. Stellar winds are a direct analogue of the solar wind. Although the astronomically observable systems have much higher mass flows, many of their spatial and temporal structures may be similar to those found in the solar wind. Thus the study of the solar wind should lead to a better understanding of, for example, mass, (angular) momentum and energy transport in these distant systems.
3. The major part of our galaxy is filled with a tenuous hot plasma, the remains of many supernova remnants. Physical processes, for example particle acceleration at shocks, growth and damping of waves, nonlinear coupling of gas and cosmic rays, heat conduction, etc., all have counterparts in shocks and waves in the solar wind.
4. Plasmas where small dust particles play an important role (either dynamically or electromagnetically or as a plasma source or sink) occur in cocoons around young stars, in some regions of interstellar clouds, and elsewhere in astrophysics; they also occur in comets and in planetary rings (of which the rings of Saturn have been observed to exhibit particularly complex phenomena, e.g. spokes).
5. 'Compact' objects in astrophysics (e.g. white dwarfs, neutron stars, also perhaps magnetic stars) possess magnetospheres, whose description in current astrophysical theory is to a considerable extent patterned after the Earth's magnetosphere. Accretion discs, a feature of many astrophysical magnetospheres, have no known direct counterpart in the solar system, but there are some similarities to the plasma discs in the magnetospheres of Jupiter and Saturn as well as to the latter's rings. In any case, the coupling between a streaming plasma and a magnetic field is an important general problem, involving reconnection, acceleration, formation of small-scale structures, etc. The rapidly rotating magnetosphere of Jupiter also has some similarities to pulsars as visualised in many models.



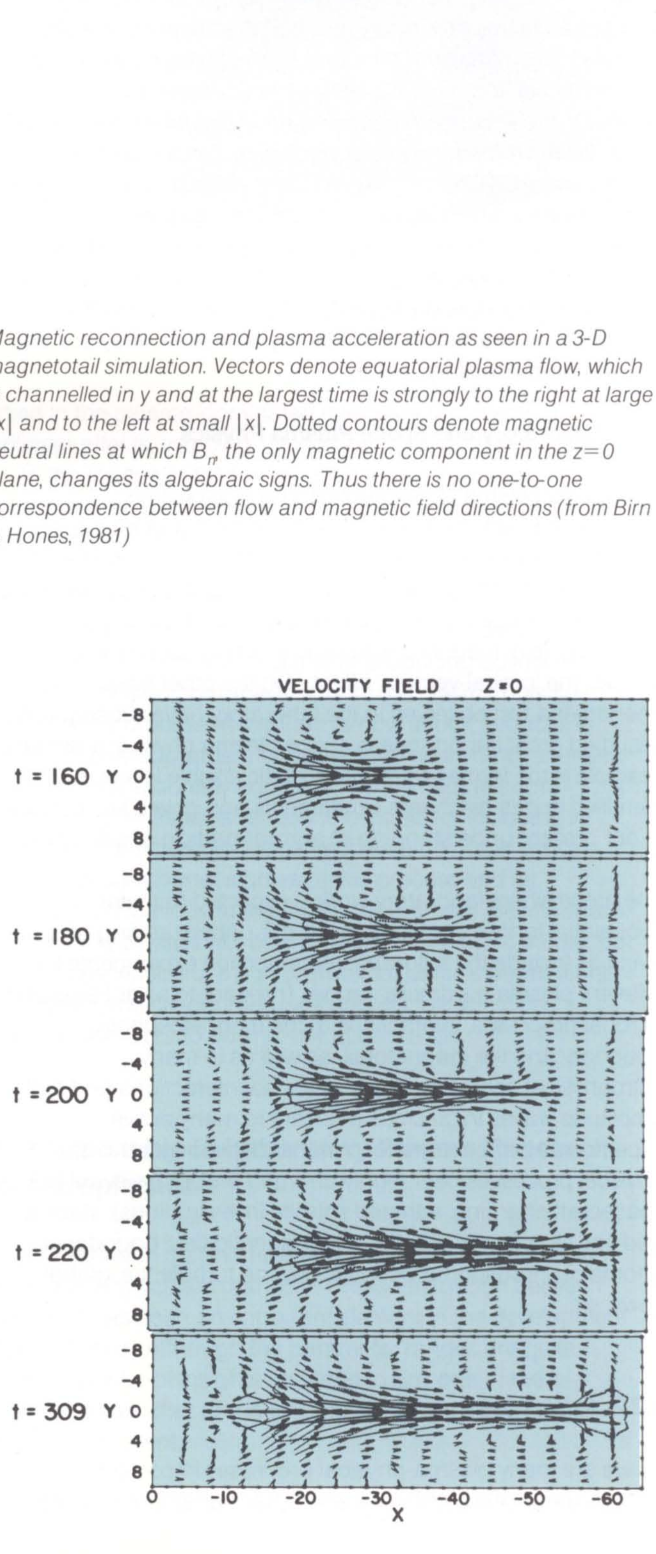
A selection of physical processes of interest in interstellar clouds (from Morfill, 1982)

6. For many astrophysical objects, a main source of information on plasma processes is constituted by their radio emissions. When collective effects of particle beams are involved in the excitation of the electromagnetic waves, close similarities may exist with the mechanisms that are at the origin of the auroral kilometric radiation, Jupiter's decametric radiation or some types of solar bursts. In-situ studies of the beams and plasma waves, where possible, are expected to provide means to finally 'calibrate' cosmic radio emissions in terms of the particle populations of their source.
7. One of the astrophysical phenomena whose obvious relation to space plasma processes has been most often quoted and exploited is the solar flare. The same basic chain of events seems to occur as in magnetospheric substorms and auroras. Firstly, mechanical energy is converted into magnetic energy; at some later stage the magnetic energy is converted into kinetic energy of plasma flows and particle beams in another part of the system.

4.3 Role of Numerical Simulation

A large number of problems in space plasmas have evolved, as a result of both in-situ observations and theory, to a point where numerical simulation of the physical system is the next logical step. A very good example of the need for this is represented by magnetospheric physics, i.e. the physics of the interaction of a flowing magnetised plasma with a planetary magnetic field. Numerical simulation has to contribute on two different levels. An MHD, large-scale description of the global system is needed, as well as simulation of important transport properties resulting from microscopic processes. Ultimately large-scale simulations should be accompanied by explicit treatment of the latter plasma processes, such as beam–plasma interactions and nonlinear development of various small-scale instabilities, in critical regions of the global system, in particular at boundaries.

Magnetic reconnection and plasma acceleration as seen in a 3-D magnetotail simulation. Vectors denote equatorial plasma flow, which is channelled in y and at the largest time is strongly to the right at large |x| and to the left at small |x|. Dotted contours denote magnetic neutral lines at which B_n, the only magnetic component in the z=0 plane, changes its algebraic signs. Thus there is no one-to-one correspondence between flow and magnetic field directions (from Birn & Hones, 1981)



Examples of notable results already obtained in numerical simulation studies are the global magnetospheric circulation patterns, the MHD picture of magnetic reconnection and, as an accompanying microscopic process, the nonlinear tearing instability. Numerical simulation of beam – plasma interactions has provided substantial clarification of the mechanism of acceleration of different ions by auroral plasma turbulence. Similarly, simulation studies of particle acceleration at collisionless shocks are presently being compared with the bow-shock data obtained by the ISEE spacecraft.

Hydrodynamic modelling of shock propagation in the heliosphere, and comparison with observations, suggests shortcomings in our understanding that will require hybrid fluid kinetic and higher moment extensions of the simulations. The importance of non-Maxwellian distribution functions, relative streaming of various species (electrons, protons, alphas etc.) and the causes of anomalous transport coefficients (thermal conductivity, viscosity and resistivity) must be assessed.

An important aspect of simulation work, which it shares with laboratory plasma physics, is the capability of isolating the individual factors that contribute to a given complex phenomenon. This is important if we wish to understand complex space plasmas, as well as astrophysical observations.

Simulation studies are at present sparsely developed in Europe. Such studies, both at the MHD and at the microscopic level, should accompany the next twenty years of research and mission planning in space plasma physics.

4.4 Future Missions

Research in space plasma physics has two aspects, that of *exploration* and that of *detailed studies of plasma processes*. In order to explore, we have to gain access to new environments, whereas the isolation of processes may be most economically performed in the easily accessible and therefore already well-studied environment of the Earth. There are, however, a number of processes, in particular those relating to neutral gas and dust-dominated high β plasmas*, which are not realised near the Earth. Their study necessarily implies a combination of the two above aspects. (At this moment it is hard to see how man could ever get direct access to an example of relativistic plasmas.) Another important explorative aspect is the confirmation that well-known processes also operate in completely different environments, naturally in different combinations and with different results and manifestations. A prominent example is the auroral acceleration process in other magnetospheres like that of Jupiter.

* The dimensionless parameter β = plasma energy density/magnetic energy density is useful for characterising magnetised plasmas.

To assure further progress in space physics, we suggest adoption of a twofold policy: (1) *well-designed exploratory missions to other plasma environments* and (2) *the use of near-Earth space as a natural plasma 'laboratory' for the study of important processes.* The latter may have to be extended to other bodies in the heliosphere which represent the closest existing examples for certain types of processes. With this policy in mind, we have inspected the responses to ESA's Call for Mission Concepts and have tried to analyse their merits and feasibility under obvious financial and technical constraints. We also attempt to fill some of the gaps left by these responses. When we are looking beyond the time covered by the present mission planning cycle, we should not forget that the latter deals with several proposals of great importance for the development of space plasma physics. In particular Soho and Cluster represent important steps in the formulation of a continuous and well-balanced policy.

4.4.1 Mainly Exploratory Missions

The space plasma missions that are largely exploratory, from the point of view of both topology and physical processes, can be conveniently divided into three main groups:

I. Solar missions
II. Inner planets and minor bodies
III. Giant planets.

We are assuming throughout that all of these missions allow interplanetary heliospheric physics to be performed singly or in conjunction with other space probes. In the following we shall highlight those aspects that make such missions exciting for space plasma physicists. We will therefore emphasise the difference in the plasma environment and indicate some of the expected physical returns, and necessary mission requirements.

In Category I, the next major project is *Soho*. The objectives of this mission are high angular and high time resolution remote-sensing of the Sun, solar seismology, etc. Due to the high data rates needed, the satellite has a near-Earth orbit. The main requirements for a follow-up plasma-physical mission, which could increase our knowledge significantly, are close proximity to the Sun ($\lesssim 10\,R_\odot$) and high data rates (temporal resolution). The maintenance of a spacecraft in close proximity to the Sun for a significantly long observation period presents severe technological problems. For general solar studies, improvements in angular resolution using a *Large Solar Telescope* in a near-Earth orbit appears more feasible. Nevertheless, in order to understand the acceleration of the gusty, inhomogeneous solar wind, it is necessary to study the properties of plasma, suprathermal and energetic particles at progressively decreasing distances from the Sun to within the Alfvénic critical point. This requires a *Solar Probe*.

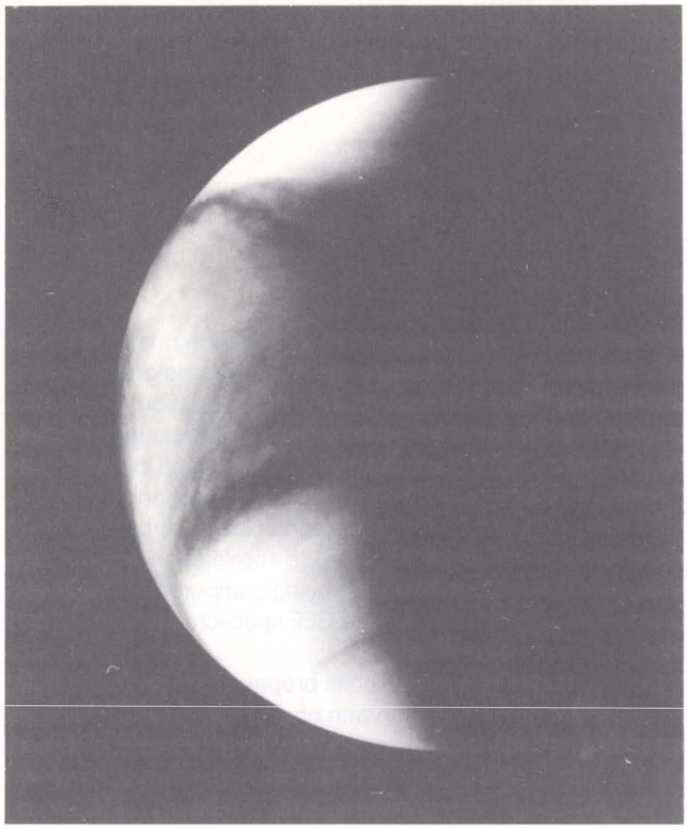


Image of Venus acquired by USA Pioneer Venus spacecraft 1978

Category II deals with the plasma environments of *Mercury, Venus, Mars, comets and asteroids.* Asteroids, whilst of great interest for the planetologist in particular in the context of the formation of the solar system, appear to be comparatively unexciting for the plasma physicist, since effects very similar to those studied near the Moon are expected to prevail.

The natural follow-up mission to Giotto seems to be a *cometary rendezvous mission* allowing long contact between the spacecraft and the cometary plasma. Apart from all the other aspects, plasma-physical observations in the tail seem to hold great promise. The environment is unique in the sense that neutral gas is embedded in and interacts with the solar wind. Properties should be strongly dependent on the comet position with respect to the Sun; of particular interest are boundary phenomena, transport of magnetic fields, macroscopic and microscopic (in)stability, the role of the solar radiation and dust, possibly also the ion-molecule chemistry. Multiple manoeuverable probes allowing high-time-resolution measurements are desirable for plasma-physical aspects.

The Venusian atmosphere, ionosphere and its interaction with the solar wind is another plasma-physical environment within reach. In order to study boundary phenomena, energy, momentum and mass transport, small-scale structures, microprocesses, etc., a *multispacecraft Venus mission* is required that can resolve spatial and temporal properties sufficiently fast. Orbit height, eccentricities and inclinations should be variable (manoeuverability), and close spatial correlation should be obtained between at least two probes. In fact, our progress in studying the Earth's magnetosphere, which has led us to consider important new steps like Cluster and the Global Geospace Mission, retain their intrinsic relevance in other parts of the solar system.

The environments of *Mercury and Mars* are poorly studied; they constitute gaps in our knowledge which should be filled. Mercury is interesting from the plasma-physical point of view, because it has a magnetosphere, but no atmosphere or ionosphere. Little is known about what processes maintain or dissipate global convection, energy transfer from the solar wind, etc. In the case of Mars, there have been many space missions. It is ironical, therefore, that we still do not even know whether Mars has an intrinsic magnetic field or not.

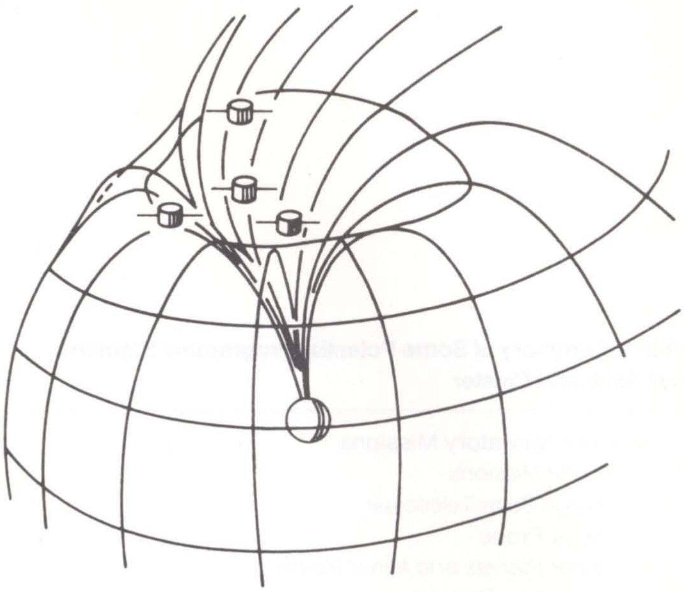
In Category III, the obvious next candidate for detailed study after Galileo is the Saturn system. Its interest lies in the interaction with satellites, in particular Titan, and, of course, the rings. From a plasma-physical point of view, both 'in-situ' measurements in the E and G rings, as well as remote sensing of the 'spokes' will provide an interesting new environment for study, namely a strongly magnetised dusty plasma. Gravitational forces may provide dynamos and a source of energy which cannot be found elsewhere. The interaction of a body containing an atmosphere with a magnetised plasma is also unique to the Saturn system. The proposed combination of a *Saturn orbiter with a Titan probe* seems a mission admirably suited for the next generation of space-plasma exploration of the outer planets.

4.4.2 Physical Processes: Small-Scale Structures

The diagnostics of fine structures in the magnetosphere are limited by observational constraints. A multi-spacecraft technique is essential, and has been used successfully in the ISEE programme. It will also be used by the three spacecraft of the AMPTE mission, and will be developed further by the proposed ESA project Cluster. The four closely grouped spacecraft of the latter mission are designed to study the three-dimensional morphology and dynamics of small-scale structures of the magnetosphere, in particular in its boundary regions, as well as magneto-hydrodynamic turbulence. The envisaged International Solar-Terrestrial Physics programme contains Cluster (as well as Soho) as important elements, while other spacecraft follow the development of physical processes on the large scale from locations in the solar wind, the geomagnetic tail and the inner magnetosphere.

The technique of using several closely grouped spacecraft should next be applied to investigations of the *auroral fine structure.* There are two reasons for assigning high priority to this research. Firstly, there is considerable interest in understanding this spectacular natural phenomenon with its small-scale structure. Secondly, it is an easily accessible site where naturally occurring charged-particle acceleration processes may be studied, processes that are undoubtedly important in many space and astrophysical contexts. Multiple spacecraft with high data rates can resolve the fine auroral spatial structures from rapid temporal fluctuations, map out

The Cluster concept — a mission under study of interest to plasma physicists



three-dimensional structures of plasma, fields and current densities, and possibly even follow the development of an auroral beam as it is accelerated down a magnetic field line.

Besides multiple-spacecraft missions, a promising practical method for conducting such studies is made possible by the proposal to deploy many *small instrumented probes from the Space Shuttle*. The scheme has technical simplicity, is cheap and requires only a short development time. Construction of individual probes is within the capability of many European laboratories, while the central facilities for deployment from the Shuttle could be provided by ESA.

4.4.3 Physical Processes: Active Experiments

Active experiments consisting of stimulation or modification of the plasma through injection of electron or ion beams, release of dense plasma clouds and generation of large-amplitude electromagnetic waves at various frequencies, are used to study basic nonlinear plasma processes involving mode excitation and wave propagation, as well as some macroprocesses such as flute instabilities. For such investigations it is essential to have extensive diagnostics on free-flying probes in the surrounding plasma.

An interesting new approach is that of *tethered satellites*, joined via tethers (up to 100 km long) to the Shuttle. Such a project is being started in a collaboration between Italy and NASA. With conducting tethers, the project opens new fields of investigation in plasma physics. Conducting tethers moving through the ionosphere can be used to set up large potential differences between widely separated magnetic flux tubes, enabling us firstly to study the interaction of highly charged bodies with plasmas, and secondly to stimulate large-scale electromagnetic perturbations, set up field-aligned currents in a controlled way, and study their properties (e.g. the so-called 'Alfvén wings'). To do this, future tethered satellite experiments should be *accompanied by extensive diagnostics on multiple probes* ejected from the Shuttle making wave and particle measurements away from it and, in particular, on the perturbed field lines.

Another concept which should be mentioned among active experiments is that of a spaceborne VHF radar for studies of irregularities, i.e. the plasma fine structure in the ionospheric F-region. Such measurements cannot be carried out from the ground at high magnetic latitudes, since normal incidence of the radiowave on the magnetic field is impossible. The power of such a radar can be low (less than ~1 kW) because of the close range of the objects of investigation. The development of such a radar could be pursued in connection with a Space Station on a high-inclination orbit.

4.4.4 Summary of Potential Programme Elements

Of the missions under study, Soho and Cluster are the ones that are of most interest to the plasma physicist. Great importance is attached to these proposals for the next major step in space plasma physics. Although each of them can stand on its own, much is to be gained if they are carried out as a European contribution to the International Solar-Terrestrial Physics programme envisaged for the early 1990s.

The subsequent table of potential programme elements addresses the period following the anticipated launch dates of Soho and Cluster (1992/93). It conveys our conviction that the future Space Plasma Physics programme should continue to maintain a balance between mainly exploratory and process-oriented studies. All the proposed exploration missions are of interdisciplinary character; other scientific communities will contribute to their detailed definition.

In general, we foresee a move to other distinctly different plasma environments for carrying out detailed process-oriented studies. The cometary rendezvous, as well as the multiple Venus orbiter concepts, are striking examples. All the same, near-Earth space will continue to constitute a convenient space plasma laboratory.

4.5 Exploitation of Existing Facilities and Need for New Developments

Many of the foreseeable or desirable technological developments are not unique to one particular space-science discipline. Nevertheless, we can list a few that would have great importance for the further development of space plasma physics.

Dilute plasmas cannot be well characterised by a few macroscopic properties like ordinary gases. A great multitude

Table 1. Summary of Some Potential Programme Elements After Soho and Cluster

1. Mainly Exploratory Missions
   - I *Solar Missions*
     Large Solar Telescope
     Solar Probe
   - II *Inner Planets and Minor Bodies*
     Cometary Rendezvous
     Venus Multiple Orbiters
   - III *Outer Planets (With Other Agencies)*
     Saturn Orbiter and Titan Probe

2. Process-Oriented Missions
   - IV *Studies of Small-Scale Structure*
     Multiple Spacecraft Studies of Auroral Source Regions
   - V *Active Experiments*
     Tethered Satellites With Multiple Diagnostic Probes*
     Space VHF Radar

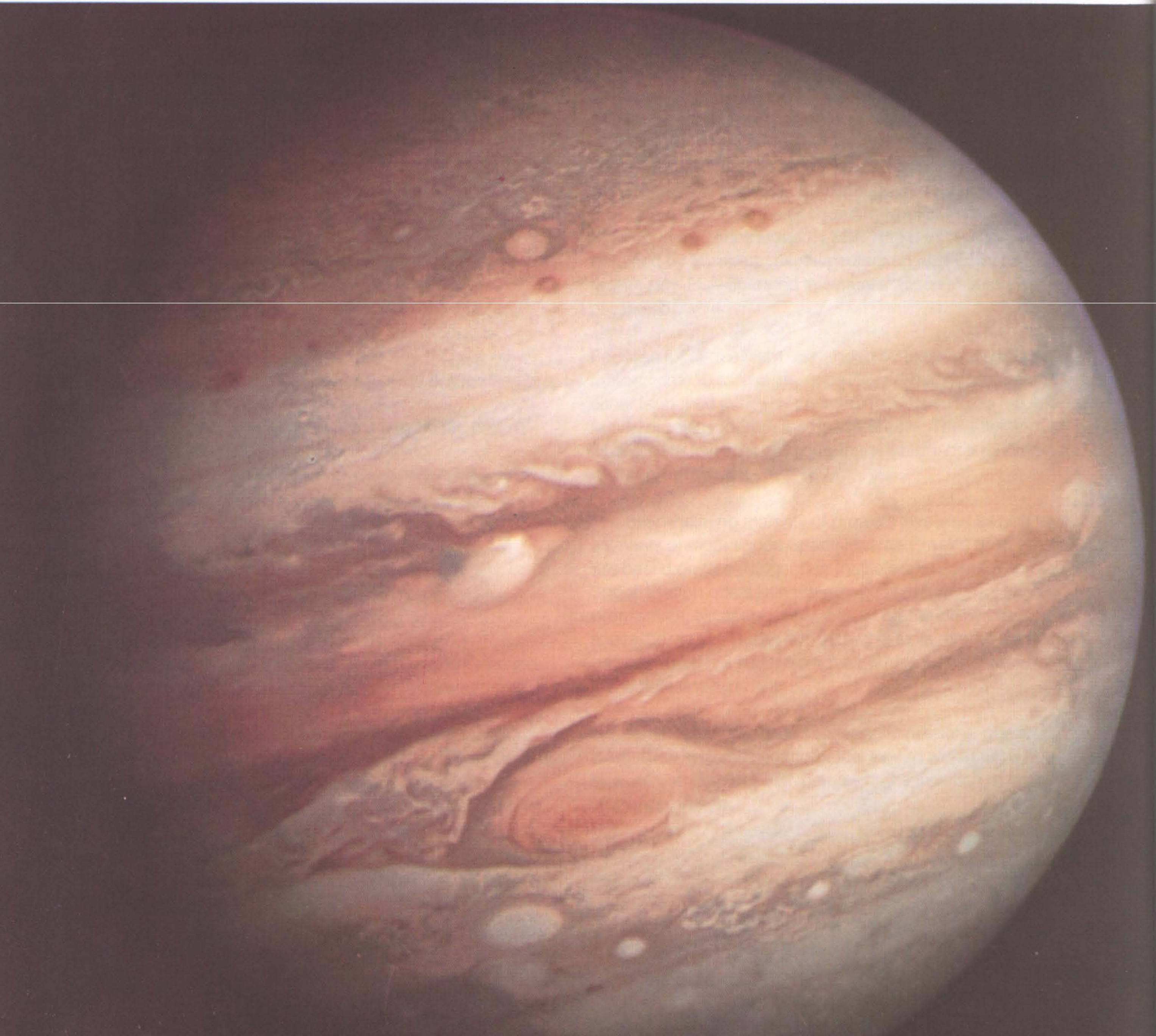
* A US–Italian programme involving tethered satellites is under way, but without the feature of multiple diagnostic probes. A facility for deploying such probes from the Space Shuttle would also be of benefit to other active or passive experiments.

of parameters, distribution functions, spectra, etc. are needed. Important consequences may result from small deviations of a particle distribution from a stable one. Therefore, there is much need for reception, transmission, storage and handling of *large amounts of data.* Onboard data-handling and storage facilities (e.g. as shock memories) have to be further developed. Telemetry stations may have to be expanded in order to read out these memories within short contact periods and cope with the data streams from multiple space probes (which are obviously in heavy demand for future plasma-physics missions). Specific attention should be paid to handling, exchange and preprocessing of such data. Whereas it is the responsibility of each individual project to secure the processing of data, the exchange of large data sets, combining space-mission data with complementary data obtained from ground-based, airborne or sounding-rocket facilities should be developed and centralised by ESA. Rapid access to data obtained by European experimenters on non-ESA spacecraft or with non-ESA-operated telemetry stations should also be organised.

Facilities for space flight demanded by plasma studies will mainly relate to availability of *multiple probes or spacecraft,* either launched jointly by powerful rockets such as the Ariane family, or released from the Space Shuttle. The latter should lend itself to low-cost missions, in the nature of sounding-rocket programmes.

The overwhelming majority of projects identified as potential elements of a continued Space Plasma Physics programme are based on free-flying, often multiple spacecraft. The planned Space Station offers little advantage in carrying out such a programme, except possibly, if in a polar orbit, by housing a space-borne VHF radar which, owing to its remote-sensing nature, would not suffer from the perturbations of the immediate environment.

For some of the proposed heliospheric missions, powerful *new propulsion systems* need to be developed which allow, for example, rendezvous with comets or the injection of multiple planetary orbiters.



Jupiter as seen by Voyager 1
Courtesy NASA/JPL.

5. Report of ESA's Topical Team on Planetary Science

Members: S. J. Bauer (chairman)
M. Fulchignoni
W.-H. Ip
Y. Langevin
F.W. Taylor
U. von Zahn

Planetary science is, by its nature, multidisciplinary. It covers not only the solid bodies of the solar system, but also their surfaces, atmospheres, and plasma- and magnetic-field environments. Thus, for example, geology (planetology), geophysics, meteorology, aeronomy and plasma physics are relevant to planetary exploration. The study of various bodies in the solar system will shed light on the origin and evolution of our solar system. These bodies range from the least-processed since their origin, such as comets, asteroids and the outer planets, to the much more evolved inner planets. Furthermore, the planets have been found at the current epoch to be highly diversified, and the same holds true for the satellite systems of the two giant outer planets. The planets also differ greatly in both the extent and composition of their atmospheres and their magnetic characteristics. With the exception of Mercury, all planets, as well as some of the satellites of the outer planets, are now known to have atmospheres. Mercury, Earth, Jupiter and Saturn, and probably Mars, have an intrinsic planetary magnetic field, whilst Venus is the only non-magnetic planet. As a result of this, the solar-wind interaction with these bodies also varies greatly: Mercury represents the case of solar-wind interaction with a planet having an intrinsic magnetic field but no atmosphere, our Moon the interaction with a non-magnetic body without an atmosphere, whilst Venus represents the case of solar-wind interaction with an ionosphere somewhat similar to that of a comet, and only the Earth, Jupiter and Saturn represent 'standard' magnetospheres.

The bodies of the solar system exhibit a wide variety of different physical and chemical properties and processes with regard to their interior structure, surfaces, atmospheres, and their plasma environment. It is the aim of planetary science to study this complex multitude with a view of learning not only about these bodies and the origin and evolution of the solar system, but also about the unique role of our planet Earth as an abode of life.

5.1 Planetary Science – An Overview

5.1.1 Small bodies and the origin of the solar system

It is now generally accepted that the formation of the solar system proceeded by accretion of dust particles in bodies of increasing size, up to kilometre-sized bodies and, finally, to planets. This accretion process stopped at an intermediate stage in the outer reaches of the solar system, as well as between Mars and Jupiter, due to the proximity of the giant planet. The small bodies of the solar system, comets and asteroids, therefore represent the last survivors of the building blocks of planetary bodies. The material constituting comets and carbonaceous asteroids is the best candidate for a pristine condensate and provides the possibility of discovering pre-solar material. This may also be true for the dark carbonaceous asteroids, while others have undergone extensive differentiation processes at a very early stage, as is evidenced by the existence of metallic and stony-type asteroids. The very different histories of asteroids of similar size, as well as the heat source required to melt such very small bodies, are major problems in terms of early solar system evolution. Indeed, multiple stages of differentiation may be required to explain the differences in chemical composition between planetary bodies.

The collisional history of small bodies should yield clues about the accretion process itself. Finally, asteroids and comets are the most likely parent bodies for meteorites, micrometeorites, and the zodiacal dust. It can therefore be argued that, at least in some cases, the sample return has already occurred. A better understanding of the environment in which meteoritic material formed and evolved will clearly increase the scientific value of this large and diverse supply of extraterrestrial material.

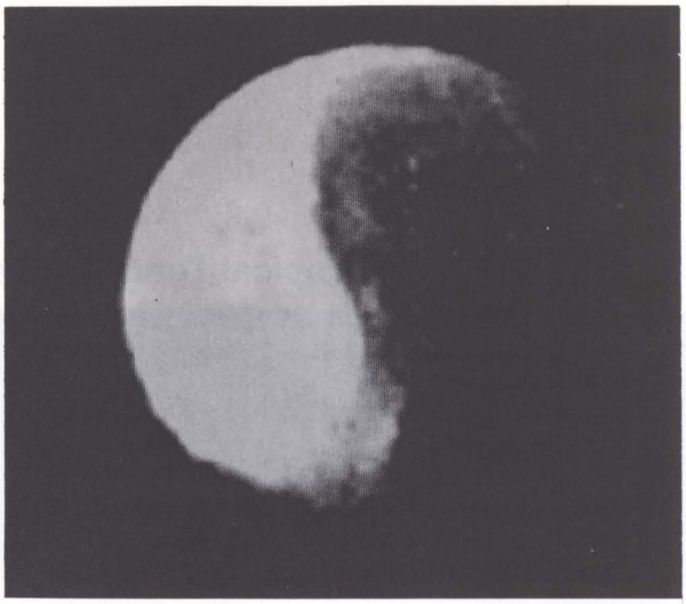
5.1.2 Planetary surfaces and interiors

The dynamical history of asteroids and comets induced collisions with planetary bodies which constitute an important process for the evolution of their surfaces. Indeed, impact craters and basins are prominent in every solid body from Mercury to the satellites of the outer planets.

Cratering history allows a relative chronology of the major events which modified the surface of a solid body, mainly in the early stages of its evolution. This process is overlapped and overlaps other processes of internal origin that play important roles in shaping planetary surfaces, i.e. tectonics and volcanism. Records of these processes can shed light on core–mantle–crust differentiation, as well as on large-scale internal fluid mass movements (connection) connected with the internal activity of the solid bodies.

Saturn's large icy satellite Iapetus - Voyager 1 photograph

(Courtesy - NASA)



A completely new problem has to be faced in understanding the evolution of large icy bodies, which show evidence of tectonic processes and possibly also volcanism. Understanding the geological and geophysical aspects of ice will be one of the major tasks in the study of the outer solar system.

Primaeval outgassing and volcanism produce an atmosphere retained by large bodies; the interaction between the atmosphere and the surface (erosion, weathering) is responsible for long-term modification of the planetary surface features. Therefore, observing tectonic, volcanic and erosional features should also provide clues about the evolution of planetary interiors.

Present knowledge of the internal structure of solid bodies is based on indirect data, such as their global dynamical properties, gravimetry, and magnetic-field structure, which are still poorly known for most planetary bodies.

5.1.3 Atmospheres

There are basically two classes of atmospheres in our solar system: the primary atmospheres represented by the large outer planets, whose composition is very similar to that of the Sun (with additional trace constituents), and the secondary atmospheres represented by Venus, Earth, Mars and the satellites of the outer planets, such as Io and, particularly, Titan. These atmospheres also show great differences in their total mass, as is evidenced by their surface pressure. There are basic unanswered questions regarding the assumed common origin, but different evolutionary paths of the atmospheres of the terrestrial planets. Did Venus ever have substantial amounts of water (similar to Earth), as seems to be suggested by the implied enrichment of deuterium? How 'massive' was an early atmosphere of Mars and what climate changes did it experience? How did Titan's nitrogen atmosphere evolve? While planetary missions to date have provided many intriguing results, they have, in turn, raised such new questions as occur particularly when comparing the different planetary bodies. To what extent may non-thermal escape processes have affected the evolution of planetary atmospheres and may again be tied to the role of the planetary plasma environment or the solar-wind interaction with these bodies?

Beyond these problems relating to the structure and composition of planetary atmospheres, there are those of their dynamics. Meteorological systems analogous to those on Earth exist in other planetary atmospheres, only with different lengths and time scales. Examples of the greenhouse effect and aerosol/dust burden currently of great interest for our own planet can be found on Venus and Mars; the influence of planetary rotation rate on atmospheric circulation can be studied by comparing Earth, Mars, Venus, Jupiter and Saturn.

5.1.4 Planetary plasma environments

The outermost boundary of a planetary environment is defined by the interaction region of either its atmosphere (in the case of an unmagnetised planet, such as Titan, Venus or a comet) or its magnetosphere (for planets with significant intrinsic magnetic fields). While there are commonalities among the physical processes of these two classes, they also exhibit striking differences. For example, the solar-wind mass loading effect causes the formation of the ion tail of a bright comet, as well as the formation of a Venusian magnetic tail; however, no definite relation could be drawn between the complex plasma structures as observed by the Pioneer Venus orbiter and those exhibited by the cometary ion tails. As a result of their large differences in the atmospheric distribution, the basic process of neutral–plasma interaction could lead to very different dynamical behaviours. In addition to its being of great interest to the space-plasma-physics community, the detailed investigation of this type of plasma environment could shed new light on the evolution of planetary atmospheres and the present dynamical behaviour and compositional structure of a number of planetary ionospheres (Mars, Venus, Titan, etc.).

For planets like the Earth, Mercury, Jupiter, Saturn and, perhaps, Uranus also, solar-wind plasma does not have immediate access to the planetary atmospheres because of the existence of their magnetospheres. The gradual inward diffusion and acceleration of solar-wind particles and of charged particles emitted from satellites, rings and the planetary atmospheres, however, introduce a variety of interesting processes, such as surface sputtering of particulate matter in the magnetospheres, and electrodynamical interactions between the planetary satellites. Last but not least, the presence of dust distributed either in a very tenuous manner (i.e. the E ring of Saturn and the rings of Jupiter) or in high concentrations (i.e. the main rings of Saturn and the narrow rings of Uranus) have led to the exciting new topic of a dusty plasma and the associated magnetospheric (or ionospheric) coupling. To some extent, the study of the early environment of the proto-planets and the solar nebula might find relevant clues from this line of space research.

5.2 Status of Planetary Exploration

During the past two decades, American and Russian spacecraft have explored our solar system from Mercury to Saturn. Planetary missions have ranged from fly-bys to landers and orbiting satellites. The emphasis for the different planets has also varied. While Mercury has only been studied by one fly-by-mission, there has been a much more detailed exploration of our immediate neighbours – the Moon, Venus and Mars. The two giant outer planets, Jupiter and Saturn, and their satellites and rings have most recently been covered by the Voyager-I and -II missions, which have provided most exciting new results.

With the exception of the Giotto mission, ESA has yet to pursue the exploration of bodies in the solar system other than Earth. Scientists in the ESA community have, however, already participated as individuals in the planetary missions of both NASA and the Soviet Union. There is a large scientific community in Europe that has strong interests and capabilities in planetary research, as documented by the European Science Foundation (ESF) ('Planetary Science in Europe – Present Status and Outlook for the Future', ESF, 1982). More than 450 interested scientists were identified in this study; the recent ESF Planetary Science Symposium in Heidelberg attracted more than 100 scientists. An ESA programme in planetary exploration could thus serve the European planetary science community, which has already made a number of specific proposals (e.g. Polo, Kepler, Asterex and Agora). More ambitious missions have been recommended by the ESF/NAS Joint Science Working Group for possible joint NASA/ESA projects, such as a Saturn/Titan mission, a multiple small-bodies rendezvous mission and an advanced Mars Rover mission.

New ideas are currently emerging from this European community, as evidenced by the responses to ESA's Call for Mission Concepts. From more than 30 submitted mission concepts related to solar-system science, about a dozen contain significant aspects of planetary science. They can be categorised as missions relating to: Mercury, Venus, the Moon, Mars, asteroids and comets.

5.3 Candiate Planetary ESA Missions

The new mission concepts proposed for a planetary programme that could be carried out by ESA *alone* fall into two categories:

i. missions of medium class (150–200 MAU)
ii. more expensive and ambitious missions (>250 MAU).

In the following we first briefly discuss possible ESA missions in these two categories. Because of financial and technical constraints, the missions in the second category could be developed into cooperative projects with other agencies. Finally, a number of candidate missions earmarked specifically for international cooperation are listed as a separate category.

5.3.1 Medium Class (150–200 MAU)

a. Mars Orbiter (Kepler)
This mission aims at greatly enhancing our knowledge about the very intriguing planet Mars. We already know of startling differences between the Earth, Venus and Mars, e.g. their atmospheres and plasma environments are entirely different. However, until much more is known about Mars, the true implications of these comparisons cannot be fully assessed. This is true in particular for two regions of Mars that have been very little explored in the past:

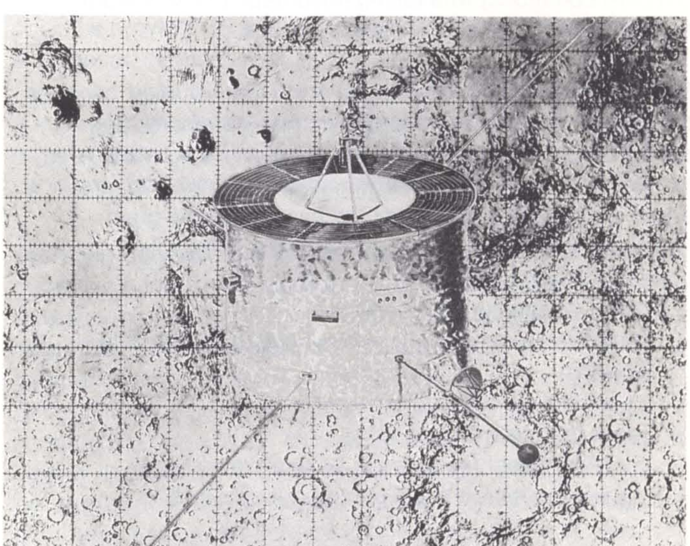
- the Martian upper atmosphere and ionosphere, their structure, dynamics, and energy balance
- the Martian magnetic field, its magnetosphere and the interactions of the solar wind with the planet,

and for a third, very important region which has been studied previously, but without adequate resolution and coverage:

- the lower atmosphere, its general circulation and principal wave modes.

The Kepler orbiter will collect extensive data in these regions, through both in-situ and remote-sensing measurements. Furthermore, the Kepler mission will considerably advance our knowledge about certain unique aspects of Mars:

Kepler - artist's impression



The Giotto spacecraft nearing Halley's comet, about four hours before closest approach. The size of the nucleus in this artist's impression is exaggerated: its diameter is in fact only about 1/50 000 of the coma diameter

- the short-term, but strong interactions between the surface and the atmosphere through massive exchanges of dust, water vapour and carbon dioxide
- the highly complex surface, its topography, possible magnetic signature, geochemistry and mineralogy
- the Martian gravity field, which contains large non-spherical components
- the photochemistry of the Martian atmosphere.

This mission would be optimised by being in orbit around Mars in the same frame as the just-proposed US Mars Geochemistry-Climatology Orbiter (MGCO). Such a 'dual-orbiter mission' would greatly enhance the scientific return through interspacecraft tracking for gravity, intrinsic versus induced magnetic field, synoptic plus detailed imaging simultaneously, and solar-wind interaction mapping, particularly if a plasma experiment could be added to the present MGCO payload. An additional benefit would be a single science group representing scientists from NASA and ESA.

b. Moon (Selene)

As has been claimed recently by the scientists interested (or involved) in the Polo assessment study, the Moon still offers a number of fascinating problems for solution.

The European planetological community maintains an interest, as demonstrated by the response to the Call for Mission Concepts: two out of the thirty six proposals deal with the Moon. One recommends a re-examination of the Polo concept, while the other proposes a new mission, Selene.

The Selene concept is somewhat different from the expensive Polo proposal: its aim is to have a low-cost mission with a well-balanced payload, trying to attract the interest of a wide scientific community and taking advantage of the heritage of the previous ESA planetary mission studies.

Several fields in Lunar Science have still to be studied, because the pre-Apollo and Apollo results left many problems only partially answered. A polar orbiter represents a scientific need to meet as many of the goals as possible, which today are easier and cheaper to accomplish because of the great improvements in space technology. Some of the scientific objectives that can be addressed are:

- lunar gravimetry and topology
- remote sensing geology and mineralogy of the lunar surface
- geochemistry of the lunar surface
- lunar magnetic anomalies
- transient phenomena (such as gas evaporation)
- plasma physics in the circumlunar environment.

c. Comet Fly-by

With the general interest in cometary research and the desire to maintain the momentum established by the ESA Giotto mission to comet Halley in 1986, future comet missions have attracted much attention. The mission concepts proposed cover a variety of approaches and hence involve a variety of mission costs.

The simplest possible scheme involves using a spare of the Giotto spacecraft for one or several fly-by observations of short-period comets. The scientific goals of such a mission would be similar to that of Giotto, but the lower flyby speed (10 to 15 km/s as compared with 70 km/s during the Halley encounter) would significantly increase the observation period. Moreover, the properties of such a short-period comet should be markedly different from those of Halley and other long-period comets. Such a fly-by mission would provide:

- the elemental and isotopic composition of the coma
- characterisation of the physical processes and chemical reactions in the cometary environment
- determination of the size distribution the chemical and isotopic composition of cometary dust
- the characteristics of the plasma environment and its interaction with the solar wind
- imaging of the nucleus with 50 m resolution.

Such a low-cost option would be compromised if additional fly-bys were performed: such a manoeuvre would require an on-board ΔV of about 2 km/s, and a mission duration of about 3 years. The propulsion system needed, larger launch mass and longer mission time would substantially increase the cost of such a mission.

d. *Multiple Venus Orbiters (Venture)*
In order to clarify the many interesting issues only touched upon by the space probes to Venus so far, a multispacecraft mission concept – 'Venture' – has been developed as the next step to investigate atmospheric and ionospheric dynamics, and to study the large- and small-scale plasma and magnetic structures generated by the solar-wind interaction with the neutral atmosphere, and last but not least, the air–surface coupling on the geologically active planet. Specifically, two or more lightweight spacecraft launched by ESA in the mid 90s would provide much-needed coverage of the macroscopic views of:

- meteorological systems
- neutral composition, distribution and thermal structure of the upper atmosphere
- ionospheric composition, distribution and dynamics
- thermal and non-thermal escapes of atmospheric mass
- magnetic field configuration
- bow shock, ionopause and other boundary regions;

and microscopic views of:

- the twisted magnetic flux ropes and the night-side magnetic holes
- plasma-wave interaction and MHD turbulence
- energy and momentum-transfers from the solar wind to the atmosphere
- magnetic reconnection processes and parallel-electric field acceleration mechanisms in a neutral-plasma environment.

5.3.2 Expensive and ambitious missions (>250 MAU)

a. *Asteroid rendezvous*
At the beginning of the next decade, asteroids will remain the only major family of unexplored solar-system objects. A first mission to study these extremely varied bodies is therefore one of the high priorities of planetary exploration.

Close-range observation of early differentiated small bodies, as well as very primitive bodies such as carbonaceous asteroids, would yield information about the very early stages of the evolution of the solar system. The collisional history of asteroids is also of great interest for understanding accretionary processes. Finally, asteroids are the most likely parent bodies of meteorites, our largest supply of extraterrestrial material. It is important to document these samples by a close look at their original geological context.

The Agora concept relies on an ionic propulsion stage, which permits up to three rendezvous with large main-belt asteroids, with a wide variety in type and size, as well as two intermediate fly-bys at a few km/s. The size, density, surface morphology and mineralogic composition can be determined during such an encounter. A rendezvous allows a much more detailed and complete mapping, as well as the determination of chemical abundances through gamma-ray spectroscopy. The scientific return of Agora would greatly improve our knowledge of asteroids, their relation to meteorites and to the formation of the solar system.

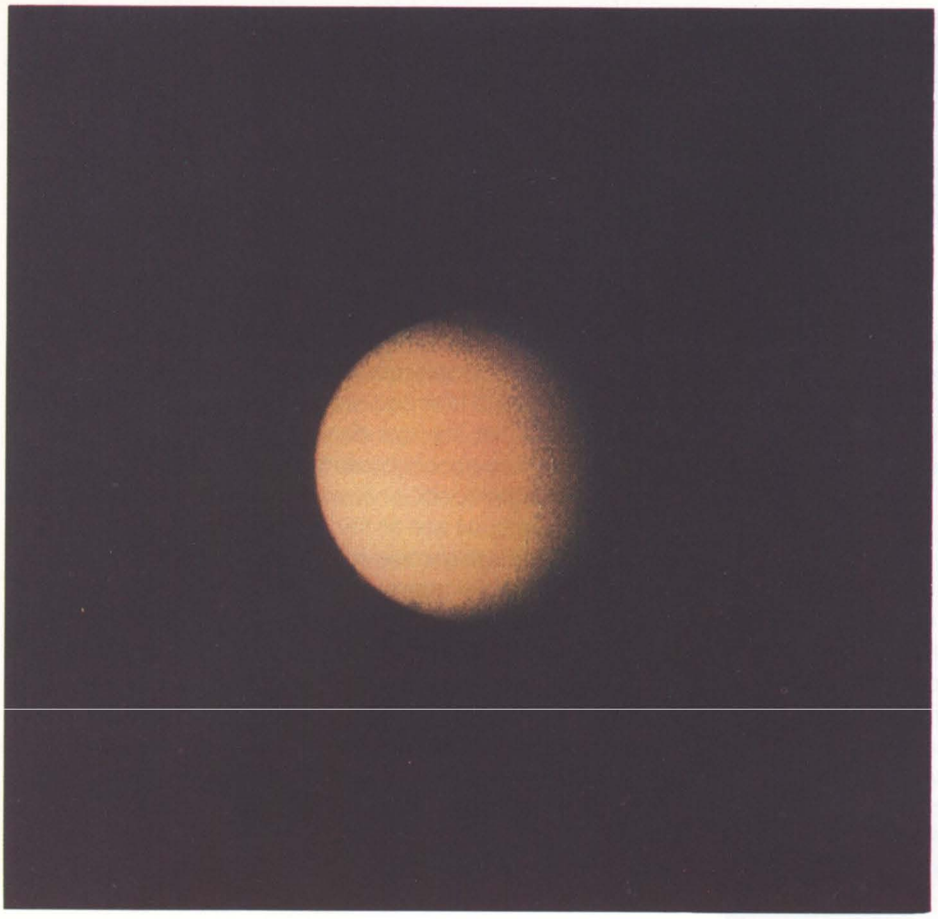
b. *Comet rendezvous*
Unlike a fly-by, a rendezvous mission to a comet provides long-term monitoring of the comet's activity as well as a much better opportunity to study the nucleus. Because of the much longer time available for in-situ measurements, many of the scientific observations could be more precise and sophisticated than in the case of a fly-by mission. More specifically, the scientific goals of a rendezvous mission are:

- determination of the chemical nature and physical structure of cometary nuclei (i.e. composition of gas and dust) and the characterisation of the changes that occur as functions of time and orbital position
- understanding of the chemical and physical nature of the dust coma, atmospheres, and ionospheres of comets as well as the processes that occur in them, and characterisation of the development of the atmospheres and ionospheres as functions of time and orbital position
- determination of the nature of comet tails and the processes by which they are formed, and understanding of the interaction of comets with the solar wind.

Such a mission requires either a large launching capability, such as the STS, or a large on-board ΔV (10–15 km/s), which could be provided by an ion propulsion system in the frame of a European mission.

A more ambitious project would be a comet/asteroid-sample-return mission, which requires ion propulsion and could be a candidate for international cooperation.

It is highly desirable to bring back samples from asteroids and comets to earth-based laboratories where an in-depth investigation can be performed with highest precision. In the case of asteroidal samples this would lead to a direct comparison with meteoritic material which is currently known through laboratory studies. Elemental and isotopic composition down to per mille accuracies are necessary to classify the material. In the case of cometary samples it is necessary to collect the material during a rendezvous mission or to bring back a drill core from the comet nucleus. This is essential in order to receive a pristine sample of cometary



The clouds covering Saturn's satellite Titan are seen in their true colours in this image taken by Voyager I at a distance of 4.5 million kilometres

Courtesy NASA-JPL

material consisting of ices and dust. Cometary material is of greatest scientific interest because it might not only contain unaltered pristine solar system material, but it might possibly contain also interstellar and stellar material (star dust), which is the case if comets are of interstellar origin or if they contain star dust of supernova remnants.

c. *Mercury Orbiter (Hermes)*
As mentioned earlier, there has been only one fly-by mission to Mercury, the innermost member of the terrestrial planets. Therefore, our knowledge about its surface topography, interior structure, chemical composition is also the least complete. A Mercury Orbiter mission could improve this situation significantly by providing extensive coverage of the geochemical and geophysical properties of Mercury by remote-sensing methods and in-sut measurements.

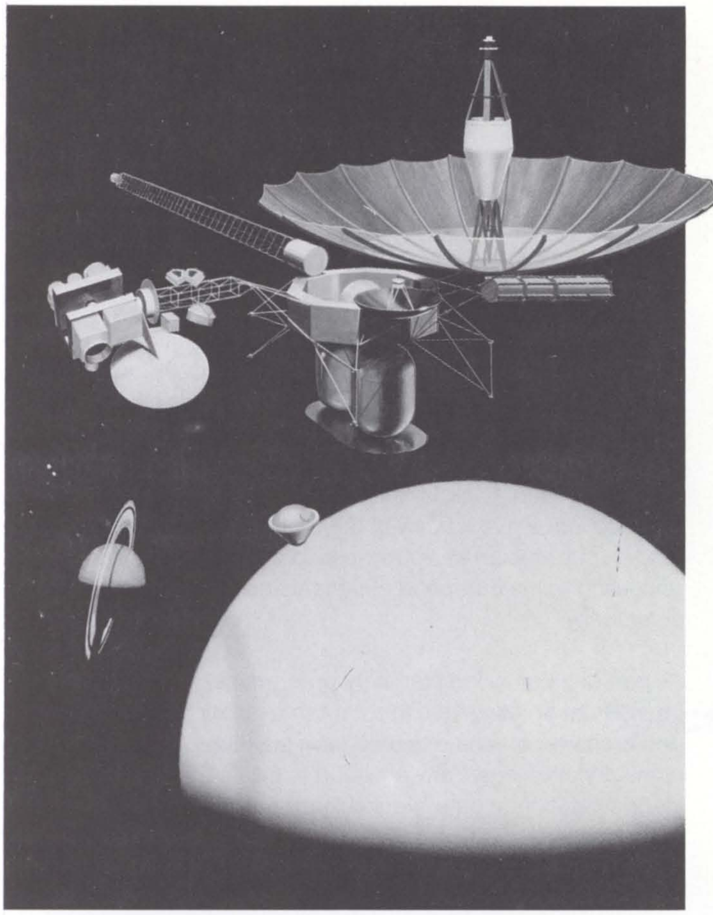
A wide variety of scientific instruments performing optical, infrared, X-ray/γ-ray spectrometry, and particles and fields analysis would be carried onboard the orbiter spacecraft in a low-altitude orbit to provide essential data on the thermal evolution, createring history, and solar-wind interaction with the planetary magnetic field.

5.3.3 Candidate Missions for International Cooperation

a. *Saturn/Titan Mission*
The Saturn Orbiter/Titan Probe mission, for which ESA and NASA have agreed to perform a joint assessment study beginning in April of this year, derives, to a large extent, from the Cassini proposal submitted to ESA in 1982. As is stressed in the Cassini proposal and in the final report of the ESF–NAS JWG Outer Planets Study Team, there are a great variety of fundamental scientific issues to be resolved by this in-depth exploration of the Saturnian system. These include the atmosphere of Saturn, its satellite system, rings and magnetosphere, as well as Titan, whose surface is surrounded by a 'thick' N_2 atmosphere, possibly containing a variety of pre-biotic molecules.

Based on the ESA–NASA discussions, the Titan probe would be provided by ESA, and the Orbiter spacecraft (Mariner Mark II) by NASA. The scientific instrumentation on the entry probe as well as the radar mapper on the Orbiter are expected to bring breakthroughs in our knowledge of Titan. The long-term observation of Saturn, its satellite system, and its magneto-spheric environment by the Orbiter spacecraft should be equally exciting.

b. *Multiple small bodies rendezvous*
Asteroids and comets are the last survivors of the swarm of planetesimals which most likely accreted into planets. Their evolution stopped very early due to their small size, and they are generally considered the most primitive bodies of the solar system. Considering the diversity and specific interest of these bodies, the primitive bodies team of the ESF–NAS JWG proposed, as the most ambitious option, a multiple-rendezvous tour, including at least one large main-belt asteroid, a short-period comet, and possibly an Apollo-Amor asteroid. Such a project requires both a large launching capability and the use of an ion propulsion system, and would be a good candidate for collaboration between ESA and NASA.



Cassini - an artist's impression of the Saturn/Titan mission. The Titan probe would be provided by ESA and the Orbiter spacecraft (Mariner Mark II) by NASA (Courtesy NASA-JPL)

c. *Mars Rover*
The term Mars Rover covers a wide class of missions. All are very expensive, very visible to the public and capable of addressing a range of first-order scientific goals. The most probable mission to be undertaken is one consisting of two or three golf-cart-sized vehicles soft-landed in areas of markedly different terrain and capable of journeys of at least several kilometres. These vehicles would investigate the morphology of the surface very comprehensively and conduct a number of experiments, including drilling for subsurface volatiles. Cheaper options have also been suggested, including a hard-landed inflatable Rover resembling a rolling ball. In general, however, it is suggested that the Rover mission is likely to be most suitable for a fresh political initiative, involving collaboration between ESA and NASA, and possibly also Japan and even the USSR.

5.4 Technology Requirements for Planetary Exploration

For the successful execution of the ESA planetary programme, there are two major areas in which new technology is required. The first is the development of an ionic propulsion capability, which is particularly well suited for inner-solar-system missions, since there the solar power density is quite large. The second one is an upgrading of the existing European facilities for communicating with planetary spacecraft.

a. *Ion Propulsion*
The interest of an ion propulsion system clearly appears when we consider the wide range of missions proposed. Indeed, the medium-class missions (Mars Orbiter, Selene and the comet fly-by missions) require up to 3 km/s on-board ΔV, and can be performed with classical propulsion. All of the other projects require either very large launch velocities (Saturn/Titan, comet rendezvous) or on-board ΔV's ranging from 10 to 17 km/s (Hermes, comet rendezvous, asteroid rendezvous, multiple small-bodies rendezvous, Mars Rover). The ion propulsion system is perfectly suited for the latter class of missions, as it circumvents the total mass and declination limitations of the Ariane launcher, with launch masses ranging from 2000 to 2500 g. The development of an ion propulsion system therefore appears as an important element for an independent European planetary program, and a possibly valuable contribution to missions in collaboration with other space agencies.

b. *Deep-Space Communications*
Existing ESA facilities are adequate for missions to the nearby planets (e.g. Kepler Mars Orbiter). Weilheim can receive about 3 kbps from 1.5 AU. The small Carnarvon and Villafranca stations can acquire 1 kbps out to 1.75 AU, and around 3 kbps from the mean distance of Venus (1 AU). For comparison, the successful Pioneer Venus Orbiter operated at 1 kbps for most of its lifetime, with short periods at 2 kbps. However, for missions deeper into the solar system, for example to Mercury, the asteroid belt or the outer solar system, they are totally unsuitable. They will also be inadequate for a high-data-rate mission to Mars, such as a Rover steered by television. Further development is clearly desirable over the next decade.

5.5 Role of Planetary Observations from Astronomical Observatories

Planetary astronomy has provided many important discoveries. Such observations are clearly complementary to a planetary programme that concentrates on the *in-situ* exploration of the planetary environments. Observations from orbiting astronomical observatories such as IUE, ST and ISO should be particularly useful for long-term synoptic observations of solar-system objects, and their use for such observations is strongly recommended. Since the main objectives of these observatories are, however, mainly astrophysical, efforts should be made to provide sufficient observing time for planetary science.

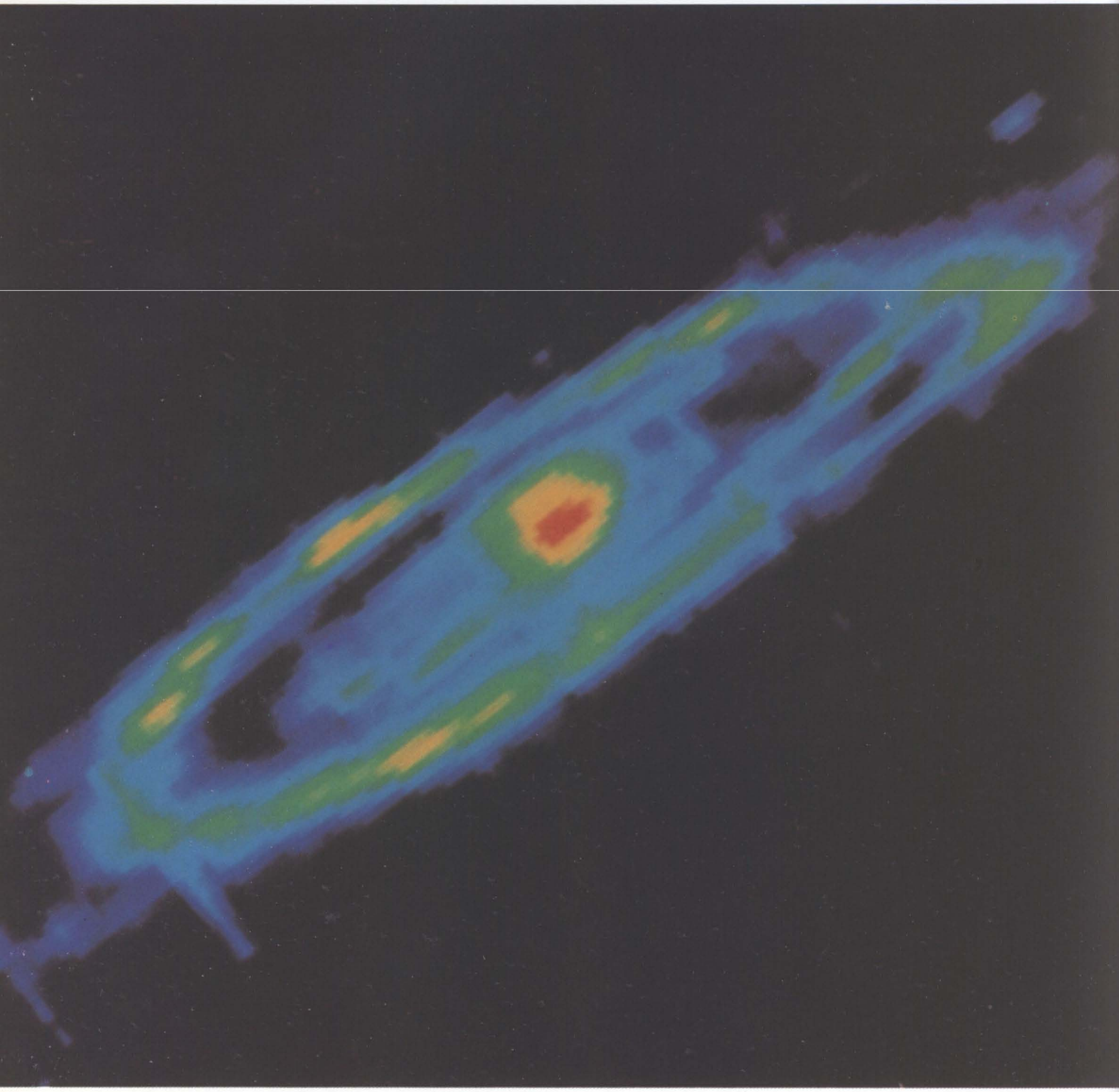
5.6 Recommendations

From the list of candidate missions discussed above, it can be seen that there is a strong interest and great potential in the European scientific community to engage in planetary exploration. While much remains to be done, we feel that the most important task is to concentrate on the ongoing activities, for example the preparation of the Kepler mission to Mars (which is now under Phase-A study) and the possible exploitation of a dual Mars Orbiter option in combination with NASA's MGCO mission. The start of the ESA–NASA joint assessment study in this year for a Saturn Orbiter/Titan Probe mission and discussions on a multiple-primitive-bodies rendezvous mission using ion-drive propulsion systems are also very encouraging. These are the most promising opportunities for European planetary scientists to actively participate in ambitious, large-scale projects with significant inputs on a wide range of issues related to solar-system research. The realisation of these joint missions within the next decade should be one of ESA's most important goals.

Suitable candidates for future new initiatives which could be performed by ESA alone include Lunar Polar Orbiter (Selene) and the Venus multiple orbiters (Venture). The next in-depth cometary exploration should be a rendezvous with a short-period comet, which could answer important questions that cannot be addressed by a fly-by mission. The development of an ion propulsion system will make possible the execution of a Mercury Orbiter mission, as well as putting the comet rendezvous and asteroid rendezvous missions within ESA's technical capability. In view of the Giotto effort, a follow-up rendezvous mission to a short-period comet is particularly appealing to the European planetary and space-science community.

As part of a European planetary programme, an effort should be made at an early date to establish a facility for the utilisation and archiving of data obtained from planetary (including cometary) missions. Early attention to this matter, including standardisation of data, would clearly avoid a waste of resources later.

Part 3 – Space Astronomy



This computer-processed IRAS image of the Andromeda Galaxy (M31) identifies regions where young stars are forming, seen here in red, orange, and yellow. Blue areas represent regions of faint infrared radiation while green, yellow, orange, and red areas, respectively, show more intense infrared emissions. Brighter areas represent regions populated by either numerous or massive young stars. IRAS observations of Andromeda represent the first extensive, high-sensitivity study of the galaxy in the infrared spectrum.

(Courtesy - NASA-JPL)

6. Space Astronomy – Survey Committee Report

For centuries, the only accessible wavelength region for astronomical observations was a tiny slit in the electromagnetic spectrum: the visual part ranging from approximately 400 to 800 nanometres wavelength (a dynamic range in energy of only a factor 2). About 40 years ago, it was established that observations in the radio domain of the spectrum (cm-metre range) were quite promising and of great potential influence on existing astronomical concepts. With the advent of the space age, the absorbing effects of the Earth's atmosphere could be entirely circumvented and the entire electromagnetic spectrum became accessible for astronomical observations: from long wavelength radio photons to hard gamma rays, a dynamic range in energy of about fifteen orders of magnitude!

It is not, of course, surprising that these new possibilities led to the discovery of a large number of entirely new cosmic phenomena and objects of a widely different character. These discoveries have drastically altered practically all concepts of our surrounding universe: from the evolution of the stars in our immediate vicinity to the physical properties and structure of the early Universe. Progress in modern astronomy and astrophysics requires in many cases a multispectral approach in which the correlation between the observed characteristics in widely different wavelength regimes is the key to the understanding of the underlying global physical properties. Since only observation from space can accommodate this wavelength coverage, it goes without saying that space astronomy constitutes the major component for present-day astronomical research.

6.1 Overview and Outstanding Problems

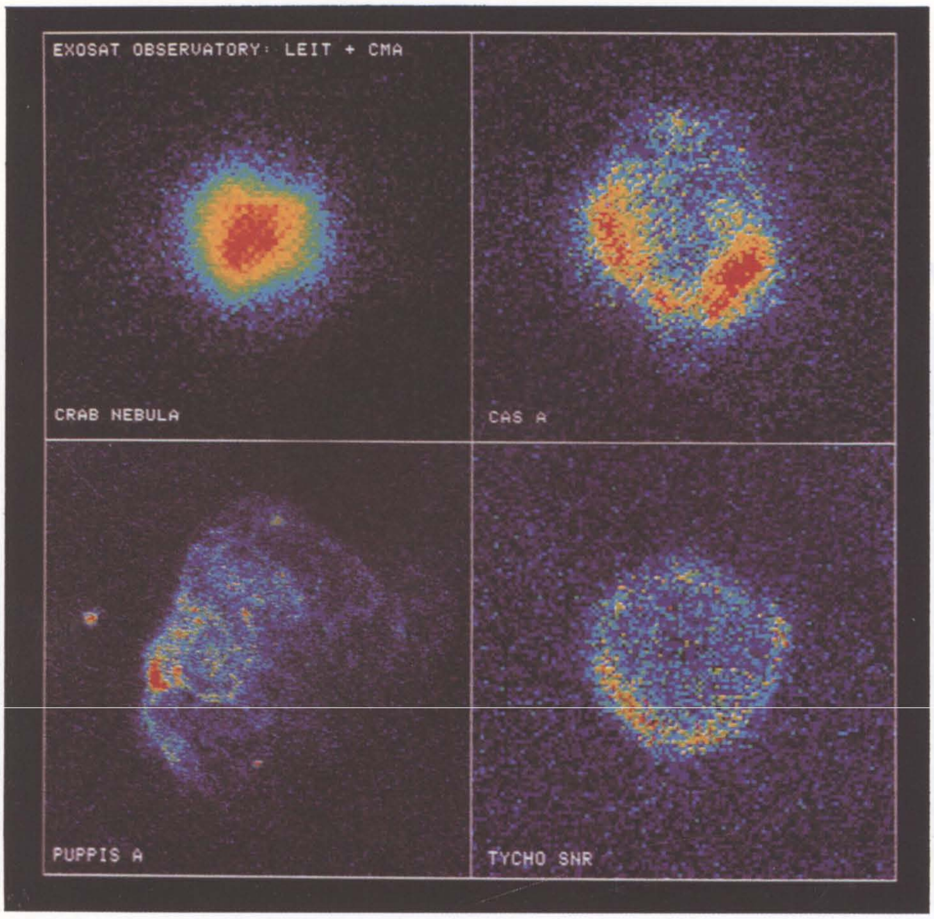
Among the present outstanding problems in modern astronomy and astrophysics are the assessment of the:
- formation and evolution of stars and planets;
- physics of compact stellar remnants;
- structure and dynamics of the interstellar medium;
- origin of the heavy elements;
- dynamic and chemical evolution of stellar populations;
- origin of cosmic rays;
- nature of the galactic centre;
- large scale structure and evolution of the Universe;
- formation and evolution of galaxies;
- power source in active galactic nuclei.

The study of most of these aspects requires spaceborne instrumentation since the important physical processes in many of these objects produce electromagnetic radiation outside the wavelength band accessible from the ground. Major topics for investigation include:

High-energy galactic phenomena
- Supernovae are believed to be responsible for the synthesis of heavy elements and thus play a crucial role in the chemical evolution of galaxies and ultimately, in the origin of the stars, of planets and of life. Supernova remnants are probably the major sources of cosmic rays which constitute a major dynamic component of the interstellar and, presumably, the intergalactic medium.
- Binary X-ray sources are seen to produce collimated jets of relativistic particles which are similar, in many respects, to those observed in active galactic nuclei and quasars, which are the most powerful sources known in the Universe.

Interstellar medium and star formation
- Half of all interstellar matter in the galaxy appears to be molecular hydrogen which can only be studied in the ultraviolet or infrared.
- Molecular masers and shocked molecular gas with temperatures above 3000 K are evidence of unusual excitation mechanisms in protostars.
- The formation of planetary systems is a direct by-product of star formation.

Stellar phenomena
- The dependence of mass-loss rate on the initial heavy element abundance may be an important clue to the understanding of the mechanisms driving the winds of early type stars.
- Large mass-loss rates of both atomic and molecular gas



in late type stars suggests that both the redgiants and the supergiants lose their entire hydrogen rich envelopes.
- The interior of stars can be probed by observing surface oscillations, and by surface spectroscopy of very massive stars after mass loss.

Background radiation
- The discovery of granularity in the microwave background will lead to important progress in the understanding of the seed inhomogeneities that eventually become galaxies.
- If it turns out that the dominant contribution to the X-ray background is due to diffuse hot gas, this will be the major baryonic component of the Universe.
- The ultraviolet background may contain redshifted line and recombination line radiation from intergalactic gas and possibly photons from the decay of exotic elementary particles.

Birth and evolution of galaxies
- The determination of the amount of deuterium, which is a direct remnant of the big bang, provides a strong measure of the density parameter and thus of the ultimate fate of the Universe.

Clusters of galaxies
- X-ray and sub-millimetre measurements of the Compton scattering of microwave background photons in the hot intracluster gas will directly yield the Hubble constant.

Active galaxies
- It is generally considered that accretion onto a massive black hole is the basic underlying process giving rise to the variations on timescales down to minutes of their enormous luminosities and outflows of mass which are often in the form of jets on all distance scales from parsecs to megaparsecs.

Relativity and gravitation
- Fundamental to our understanding of gravity is the testing of the frame dragging effect of spinning, as compared to non-spinning bodies.
- As gravitational waves emitted by collapsing supermassive stars move through the solar system, they perturb the relative position of the Earth and a suitably distant orbiting satellite. Detection of gravitational waves would open a new era in astronomy.
- General Relativity agrees with experiments in the weak field limit. More accurate experiments are needed to test non-linear effects of theories of gravity and to measure the solar quadrupole moment.

6.2 Mission Concepts, Identification of Programmatic Elements

For Europe to make a first class and well-matched contribution to the progress of astronomical research in the areas highlighted in the previous section, its future programme in space astronomy should be assessed by evaluating its present position in the worldwide context of space astronomy and by further exploiting specific European capabilities and interests (as evidenced by the responses to the Call for Mission Concepts).

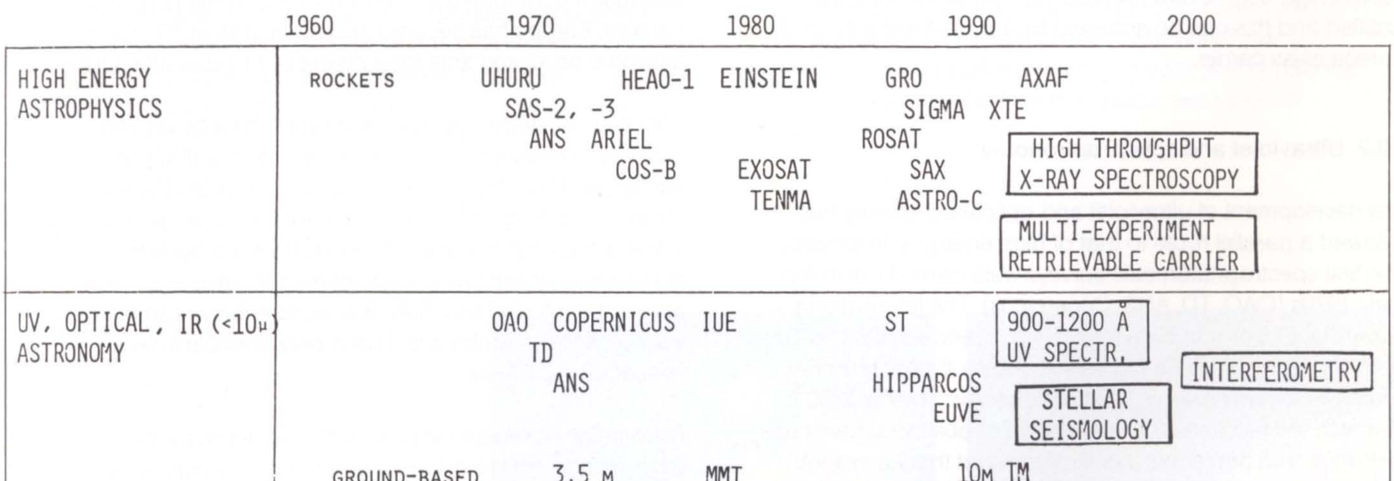
Assessment of Europe's present position and future perspective can best be done by a description of developments in the technique oriented disciplines of high energy astrophysics, ultraviolet and optical astronomy, infrared and sub-millimetre astronomy and radio astronomy. An overview of the historical development and a perspective for the future are given in the chart below.

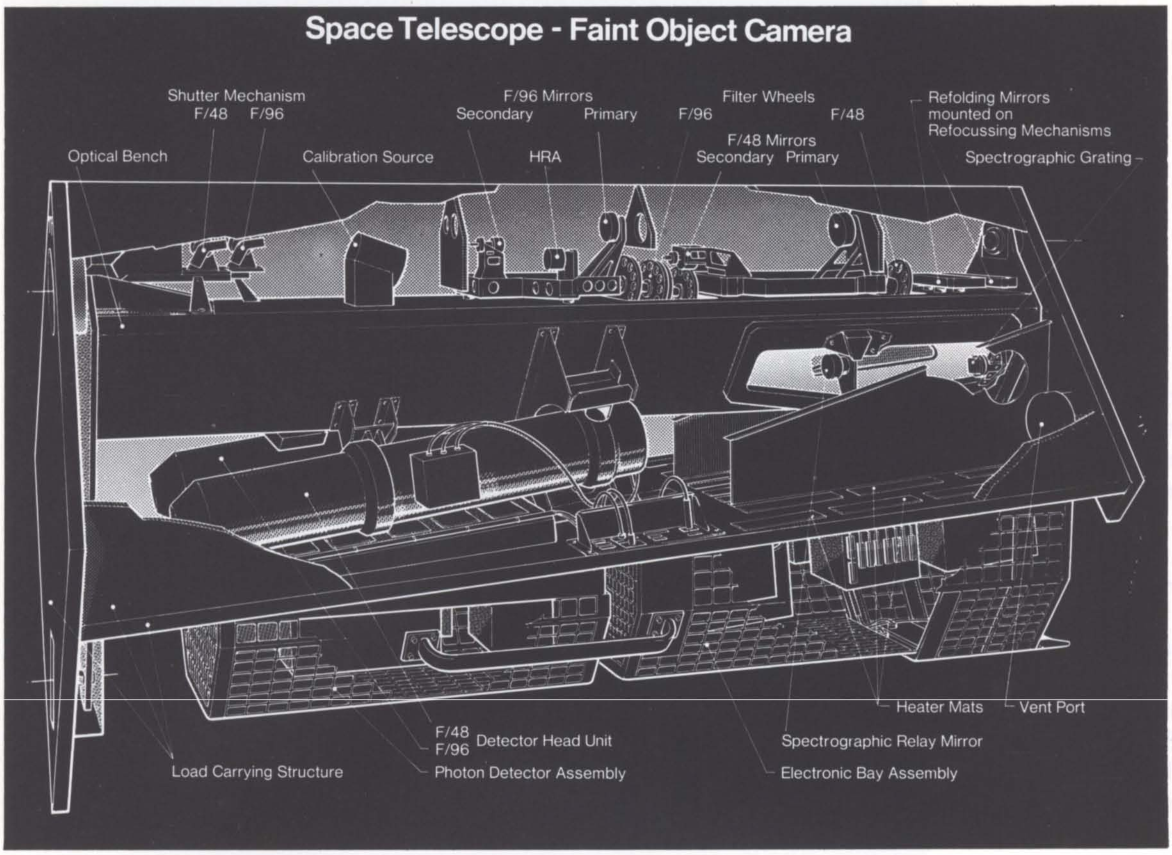
6.2.1 High energy astrophysics

This field of space research is the most advanced in its development. The very promising rocket experiments in the 1960s led to the first surveys carried out in the early 1970s (UHURU, SAS-2, 3, ANS, ARIEL-V). The second generation of X-ray missions began with the flight of the Einstein satellite which was capable of providing the first high resolution X-ray images of weak cosmic sources. In these first and second phases, Europe has been, and still is, playing a very important role. In addition to the ESA programmes (Cos-B, Exosat), individual Member States are planning specific missions tailored to the interest of their own scientific community: a soft X-ray all sky survey by Germany (Rosat), a hard X-ray spectrophotometric mission by Italy (SAX) and a gamma-ray imaging mission by France (Sigma). A limited X-ray spectrophotometric satellite (Tenma) has been launched by Japan and will be followed up by an X-ray timing mission (Astro-C). Within the United States, a multi-experiment X-ray timing mission (XTE) is part of the Explorer programme.

The scientific achievements and technical developments in high energy astrophysics now fully justify the development of third generation observatory class satellites which are expected to provide an improvement of a factor of 10 to 100 in sensitivity, spatial or spectral resolution, or number of objects studied. Within the United States, one such mission in the hard X-ray and gamma-ray region is under development (GRO), and in the soft X-ray region another mission is under consideration with high priority (AXAF). With the existence of GRO, an additional effort by Europe in the gamma-ray domain is not justified. In the X-ray region, however, a complementary mission to AXAF deserves high priority. It is important to recognise that the emphasis of AXAF observations will be on deep surveys with the highest possible spatial resolution. In order to investigate the physical processes governing the sources accessible to AXAF, spectroscopic studies with similarly high sensitivities are required. Europe could contribute these by developing a high throughput X-ray spectroscopy observatory.

Space Astronomy Missions





Courtesy Dornier

Within the European high energy astrophysics community, there is also a strong interest in carrying out experiments dedicated to specific scientific goals. The responses to the Call for Mission Concepts can roughly be divided into two groups associated with soft, and hard X-ray plasma diagnostics respectively. The quality of the research in these areas is of such a high degree that frequent flight opportunities are justified and this can be achieved by frequent reflights on a Eureca class carrier.

6.2.2 Ultraviolet and optical astronomy

The development of ultraviolet and optical astronomy has followed a parallel route to that of high energy astrophysics. The first spectrophotometric surveys were carried out in the early 1970s (OAO, TD, ANS, Copernicus). The International Ultraviolet Explorer (IUE), a joint mission between ESA, NASA and the UK, is still operating very successfully. Antireflective coated windows prevents IUE from observing below 1200 Å; however, the fundamental importance of observing molecular hydrogen and deuterium, necessitates that this wavelength region be accessible with adequate sensitivity.

The Space Telescope (ST) will not be sensitive in the 900 – 1200 Å wavelength region, and therefore as a follow-up to IUE and as a complementary mission to ST, there is a need for a space observatory in the 900 – 1200 Å wavelength region which will be able to study the morphology of molecular hydrogen and deuterium. Europe has the required expertise to make a major contribution to such an observatory.

In the visual part of the electromagnetic spectrum, the Space Telescope is expected to dominate astronomical research for decades. Considering its sensitivity to faint objects, which is several orders of magnitude better than possible with the largest ground-based telescope, it can be expected that most of its observing time will be spent on extragalactic research. Because it contributed the solar arrays and the faint object camera, Europe has secured access to at least 15% of the available observing time for a period of 11 years after launch.

The study of stellar structure and evolution requires very accurate measurements of radial velocities and brightness variations. The influence of the turbulence in the Earth's atmosphere limits these measurements from the ground to only a few of the brightest stars. An increase in photometric accuracy of at least two orders of magnitude is required to assess the internal structure of a representative sample of the various stellar populations. This is only possible from a spaceborne platform.

Astrometric observations provide the yardstick for the determination of the distance scale of the various objects in the Universe. The European satellite Hipparcos will improve the accuracy of the astrometric parameters by at least two orders of magnitude and thereby improve the baseline for the distance scale dramatically. Hipparcos will provide the largest systematic catalogue of stellar positions and parallaxes with unprecedented accuracy, also the largest systematic two-colour photometric catalogue.

Post Space Telescope and Hipparcos visual astronomy should be defined in the context of the evolution of ground-based astronomy. At the end of the 1980s, a 10 m tessalated mirror telescope is expected to be operational in the United States. Also within ESO, plans for a new generation large optical telescope system are advanced. Within France, the first successful observations using an optical interferometer have been made. These developments indicate that the long term future of optical space astronomy is undoubtedly in the direction of interferometry.

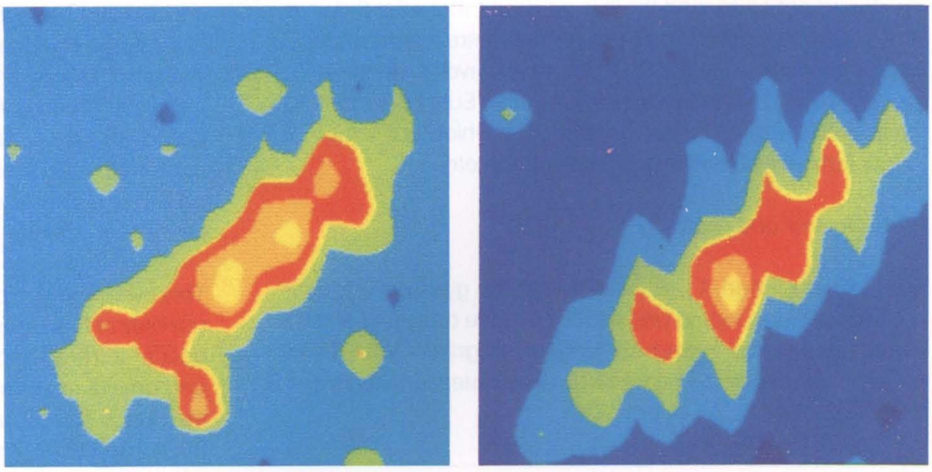
6.2.3 Infrared and sub-millimetre astronomy

Over the last 15 years, infrared astronomy has proved its scientific potential in all fields of astrophysics. Many of these achievements have been obtained with modest instruments mounted on balloon-borne and airplane telescopes. For all these observations, the results have been limited by the characteristic opacity of the residual atmosphere. The first infrared photometric sky survey made in the early 1980s with the US-NL-UK satellite IRAS has provided the astronomical community with an overwhelming amount of fascinating data. Detailed spectroscopic investigation of the objects discovered with IRAS is now urgently required; the first steps in this direction will be made using the German Infrared Laboratory (GIRL), to be flown on the Shuttle in the second half of the 1980s (observations of the brightest sources only). The Spacelab-2 mission, expected to be launched in 1985, will contain a small liquid helium cooled telescope which will study galactic regions at low spatial resolution. In addition, it will provide information on the quality of the Shuttle environment for infrared observations. This experiment is provided by US investigators. Collaborative plans between France and Germany for an infrared/sub-mm telescope mounted in an Airbus (Astroplane (AP)) are well advanced.

The Infrared Space Observatory (ISO), to be developed and launched by ESA in the early 1990s, will follow up these measurements with a wide range of infrared instruments. The orbit selected will allow ISO to achieve a performance restricted only by the fundamental limits imposed by the natural background emission which is due to the zodiacal light. A similar observatory-type mission (SIRTF) is under consideration by NASA. Although originally designed as a Shuttle attached facility, it is now considered as a free flyer in a 900 km polar orbit. Its development may depend on the timely availability of servicing vehicle capabilities under consideration in the US Space Station programme.

The sub-millimeter wavelength region is the last major unexplored part of the electromagnetic spectrum. Observations in this wavelength region are seriously hampered by absorption in the Earth's atmosphere. Towards the end of the 1980s, NASA will launch the Cosmic Background Explorer (COBE) to map the large scale distribution of the cosmic background at sub-mm wavelengths. On a much longer timescale, NASA is studying a Large Deployable Reflector (LDR) which is expected to cover the wavelength region between 0.03 and 1 mm using a 20 m telescope. Such a system would depend on presently undeveloped technologies, and would also require human assistance for antenna deployment in space.

Present European developments in sub-millimetre antenna technology permit the development of a timely mission in sub-millimetre heterodyne spectroscopy as an intermediate step, which would provide the European scientific community with a unique opportunity to take the lead in studies of star and planetary system formation, origin and evolution of galaxies and small scale granularity of the cosmic background radiation.



Infrared images produced by IRAS, of NGC 891, a disk galaxy similar to our Milky Way

(Courtesy ICIRAS)

6.2.4 Radio astronomy

The development of aperture synthesis techniques allowed the construction of radio interferometers. Since the beginning of 1970, the Westerbork Radiosynthesis Telescope (WSRT) in the Netherlands, the 5 km interferometers at Cambridge and the Merlin network in the UK, and the Very Large Array (VLA) in the US have become operational. Transcontinental interferometric measurements have provided radio maps of a few of the brightest radio sources with an angular resolution limited only by the longest baselines achievable on Earth. Within Europe, the radio telescope are now being used very successfully for part of the time as elements in an interferometric network (EVN). Towards the end of the 1980s, the Very Long Baseline Arrays (VLBA) consisting of a network of 10 telescopes spread widely over the United States will provide observations with a three order of magnitude increase in spatial resolution. In addition, a ground-based network will be developed on the Australian continent. With these observing facilities completed, the limits of angular resolution using Earth-based baselines will be reached towards the end of the 1980s.

European and American radio astronomers have a strong interest in a spaceborne radio telescope in an elliptical orbit which, when linked to both the European and American ground-based networks, would provide images with unprecedented angular resolution. Within the Soviet Union, plans also exist for a radio telescope in a highly eccentric orbit. Europe has at present the required scientific and technological potential to play a major role in joint space VLBI programmes.

From the mid-1980s onwards, ground-based millimetre telescopes will become operational in Europe and in the United States. The first telescope within the French/German collaboration in IRAM will become operational very soon. A collaborative effort between Sweden and ESO will provide a millimetre telescope (SEST) in the southern hemisphere in the second half of the 1980s. Millimetre interferometry is being developed right now and there is no doubt that after the year 2000, there will be a strong push for millimetre interferometry using spaceborne elements. Through its developments in ground-based millimetre radio astronomy, Europe is creating the scientific and technical infrastructure which justifies a longer term investment in space interferometry.

6.2.5 Gravity and relativity

About 20 years ago, it was predicted that a gyroscope in orbit around the Earth would precess. This frame dragging effect is a thus far untested aspect of the theory of gravity. Within the United States, such an experiment, designated Gravity Probe B, has a high priority.

Scientists in Germany and Italy have been deeply involved for many years in the, so far unsuccessful, search for gravitational waves. Fluctuations in range and range rate measurements between the Earth and a distant satellite might lead to the discovery of such waves. Two frequency ranging of an accurate clock on a satellite close to the Sun would measure the second order redshift and solar quadrupole moment, thus testing the non-linear effects of the theories of gravity.

Apart from the gyroscope experiment, for which a dedicated satellite is under consideration within NASA, the aforementioned experiments can be carried out as passengers on missions devoted to other purposes, in particular on deep space missions for solar system research. A clock in a deep space mission could lead to the detection of frame dragging effects by measurement of one way time delay.

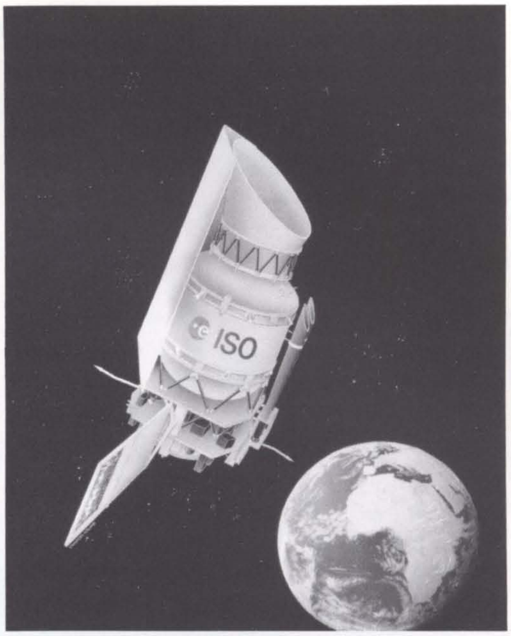
6.3 Community in Europe

Over the past two decades, the community in Europe involved in the discipline of space astronomy has evolved strongly. This is best explained by considering the various phases in the development of this new branch: the pioneering phase, the exploration phase and the exploitation phase.

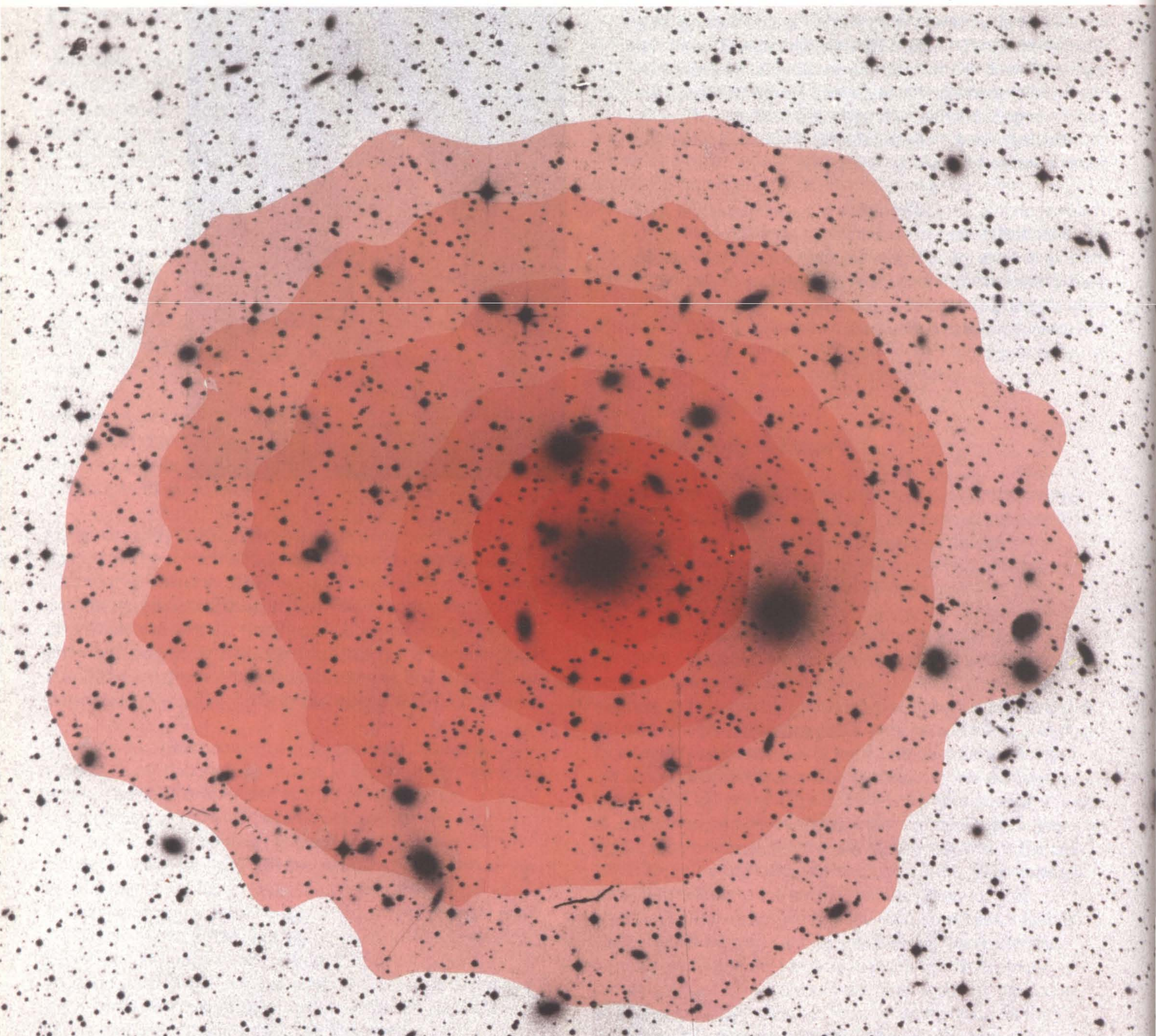
In the beginning, the main stimulus was provided by the persistent efforts of a few pioneering scientists with the intellectual and technical resources at their disposal. For example, in the area of high energy astrophysics, practically all the experiments in the early 1960s were carried out successfully by a limited number of mainly hardware-oriented institutes in the various Member States. The success of these pioneering experiments led in the 1970s to the involvement of small groups of astronomers mainly in space science laboratories, in the preparation and evaluation of sky survey missions. In the late 1970s and the early 1980s, the first observatory-class satellites became available to the entire European astronomical community. The easy access to the data from these satellites has attracted wide and strong interest from many scientific groups which were not involved in the development of the instrument hardware. For example, recent calls for observing proposals on IUE and Exosat have attracted responses from more than 100 different scientific institutes. The time available on IUE and Exosat was over-subscribed by a factor of five to ten at every call for observation proposals.

This evolution is expected to continue in the 1980s and 1990s, not only in high energy astrophysics, but also in ultraviolet, optical, infrared and radio astronomy. Progress in ultraviolet and optical astronomy will be dominated by observations with the Space Telescope (ST). The Infrared Space Observatory (ISO) and SIRTF (if approved), following the discoveries of IRAS, will undoubtedly provide many surprising and exciting results. With the availability in the 1990s of observatory class facilities, such as ST and ISO, the boundaries between the technique-oriented astronomy and astrophysics will gradually dissolve and the large European astronomical community will be critically dependent on the availability of an adequate space component for this scientific discipline.

The investments, not just financial, but also intellectual, made over the past 25 years in the European astronomical community have made it possible for European scientists to make prominent contributions to the progress of our understanding of the Universe. It is our obligation to ensure that this continues to be the case.



ISO



Contours of diffuse X-ray emission in the Perseus Cluster of galaxies superimposed on an optical image. The X-rays were detected with the Einstein Observatory and originate in the hot (80 million K) intracluster gas. A cooling flow of this gas is taking place onto the central galaxy, NGC 1275, at a rate of about 300 $M_{\odot}\ yr^{-1}$.

7. Extragalactic Astronomy from Space in the 1990s

A.C. Fabian

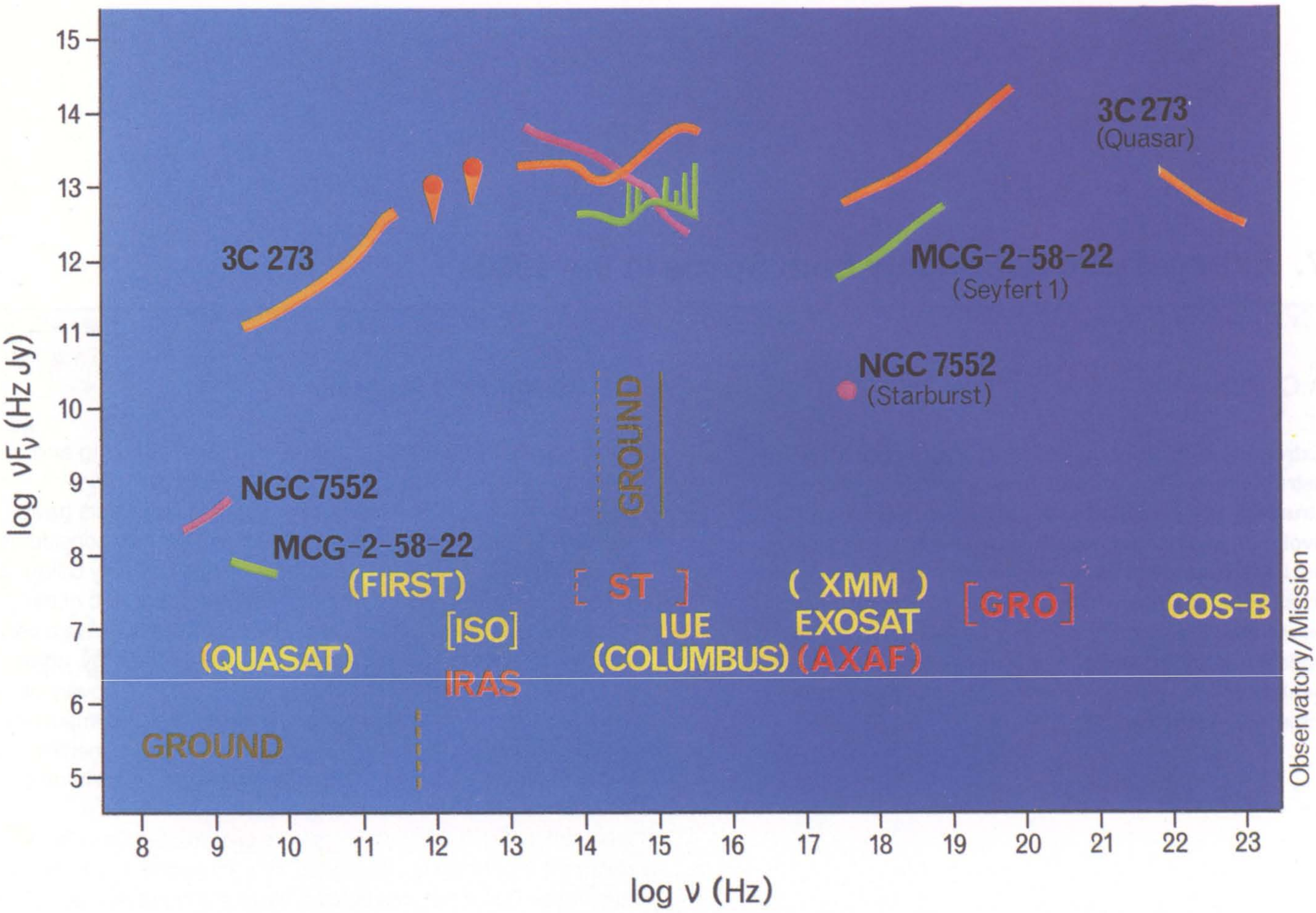
Extragalactic astronomy presents major problems for astronomers. Chief among these are the large-scale structure and evolution of the Universe, the formation and evolution of galaxies, and the power-source in active galactic nuclei. The study of many aspects of these problems requires spaceborne instrumentation. Ground-based telescopes are restricted to only two wavebands, in the optical and radio, which do not necessarily coincide with the peak of cosmic emissions or the region where the spectral information is richest.

7.1 Background Radiation

The *background radiations* provide ways of measuring and isolating all of the major problems met in extragalactic astronomy. Many observations over the past sixty years have shown that the Universe is expanding. It is generally considered that it originated in a hot Big-Bang some ten to twenty billion years ago. The *microwave background* is a direct relic of the early fireball phase. Current observations show it to have a very smooth blackbody spectrum in both space and energy, apart from a dipole signal induced by our motion. The discovery of granularity in the microwave background will lead to important progress in our understanding of the seed inhomogeneities that eventually became galaxies. The shape and amplitude of these perturbations is currently a matter of theoretical speculation. Such measurements are best made from space, where the whole sky is observable and atmospheric effects are minimised. This is particularly important in the *submillimetre spectral region* around and above the peak of emission which is completely absorbed by our atmosphere. A far-infrared telescope is capable of making the observational breakthrough.

The *X-ray background* is the integrated emission from all sources of X-rays and probably originates from within a red shift of about two to ten. The dominant contribution may be active galaxies, a hot intergalactic gas, or some as yet unknown class of source such as young galaxies. If it is due to a diffuse hot gas, then that will be the dominant baryonic component of the Universe. Whatever its origin, the spectrum and fluctuations of the X-ray background constrain the X-ray evolution of galaxies and the distribution of matter on scales of between 100 and 1000 Mpc. Existing data on the faint sources that can potentially constitute the X-ray background obtained with the Einstein Observatory is restricted to the spectral band below 3 keV, whereas the characteristic energy of the background is about 40 keV. A high-throughput X-ray spectroscopy mission will make sensitive spectral observations of all known types of X-ray sources over a much wider range, and can thereby identify the components of the background.

Other extragalactic background radiations have yet to be detected with certainty at the infrared, optical and ultraviolet wavebands. The ultraviolet background may contain red-shifted line and recombination radiation from intergalactic gas and possibly photons from the decay of exotic elementary particles.



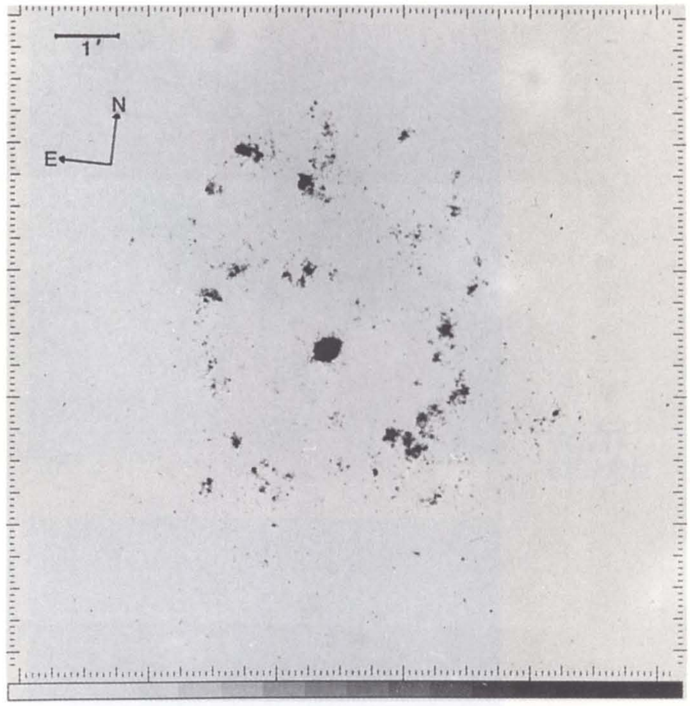
Spectra of 3 Active galaxies displayed over 14 decades of frequency. νF_ν is a measure of the total power radiated in each frequency band. 3C273 is a radio-loud quasar; note that much of its bolometric luminosity emerges around 1 MeV. MCG-2-58-22 is a typical Seyfert 1 galaxy and NGC7552 is a starburst nucleus. Representative emission lines in the optical and UV are shown only on the spectrum of MCG-2-58-22. Some existing, planned and proposed missions are indicated at the bottom.

7.2 Galaxies

Galaxies are visible optically because they contain many stars. Their evolution, however, relies on gas flows that are best detected at other wavelengths. Far-infrared spectroscopy will probe deep into the gas clouds within which stars form. X-ray observations will map the hot interstellar medium and supernova remnants enriched in heavy elements. The interstellar medium in an elliptical galaxy may only be detectable through its X-ray emission.

Detailed spectra of the stars and gas in galaxies over all wavebands are needed for stellar-population synthesis and abundance studies in order to understand galactic evolution. The amount of deuterium in the Universe is another direct remnant of the Big-Bang. It provides a strong measure of the density parameter and thus of the ultimate fate of the Universe. This can be measured from its absorption in ultraviolet spectra. The formation of galaxies and their emergence as self-luminous entities is very uncertain. The red shift means that the normal stellar population of a very distant galaxy is not readily observed at optical wavelengths, but should be sought in the infrared. Results from the IRAS satellite, which gave the first all-sky survey at these wavelengths, may contain the first indications. Deep follow-up studies with ISO will be able to pursue this. It has recently been discovered that nearby regions of active star formation are visible at all wavelengths from the radio to X-rays. Careful searches for primordial galaxies must therefore be made throughout the entire spectrum. It is highly likely that the discovery and understanding of the galaxy formation process and the early evolution of galaxies will require observations only available from space.

Clusters of galaxies are prominent X-ray sources due to hot intracluster gas. The mass of this gas is comparable to that of the visible galaxies. Most of the cluster mass is, however, still undetectable, except through its gravitational influence. This 'hidden' mass appears to be a common constituent of the Universe and it is clearly important that we understand its nature and origin. It may consist of dead stars, or stars of very low mass. Alternatively, it may be due to massive neutrinos or to some other fundamental particles remaining from the Big-Bang. The X-ray emitting gas provides an opportunity for measuring the local gravitational potential within clusters, since it must be close to hydrostatic equilibrium. X-ray observations can then be directly translated into the matter density and 'hidden' mass profile of a cluster. In particular, this can be carried out in the core of the cluster where there are too few galaxies to act as useful probes of the potential. The elemental abundances of the intracluster gas are also important for they contain clues to early enrichment. For example, there may have been an early and widespread phase of massive star formation when the Universe was less than a billion years old and galaxies had not yet separated out. The intracluster gas may



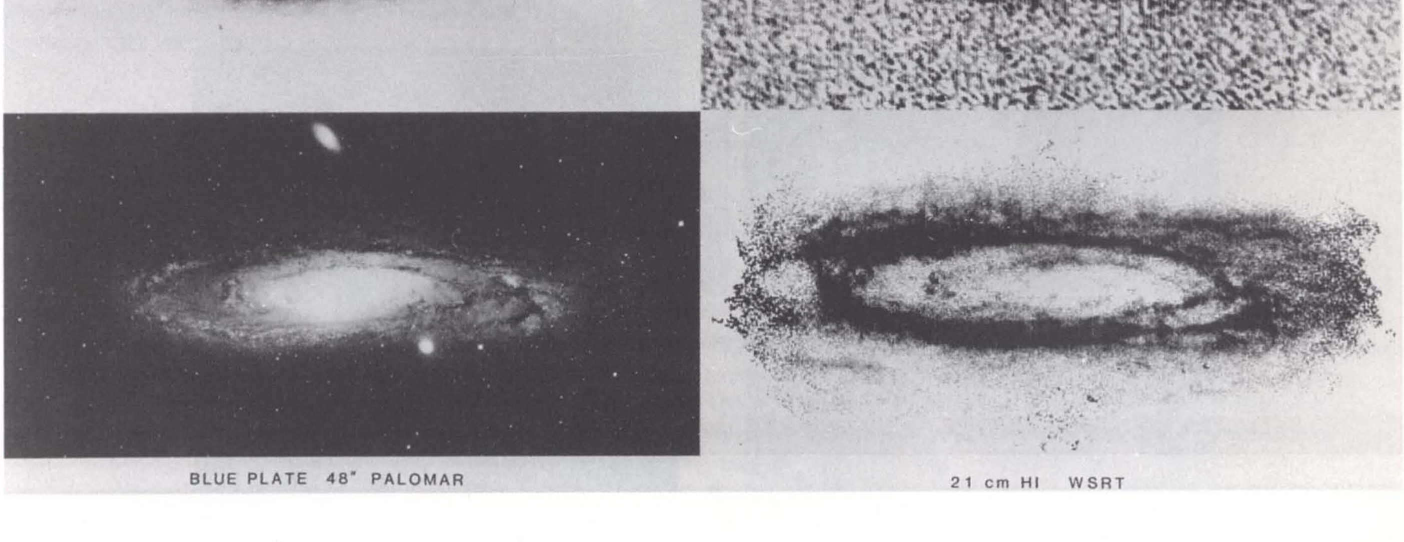
The galaxy M83 in the 1540 A band taken with a 38 cm rocket-borne telescope (Bohlin et al., 1983. Astrophys. J. 274, L53). Note the clumps of massive young stars in the spiral arms. The nuclear emission is extended and is probably due to a burst of star formation.

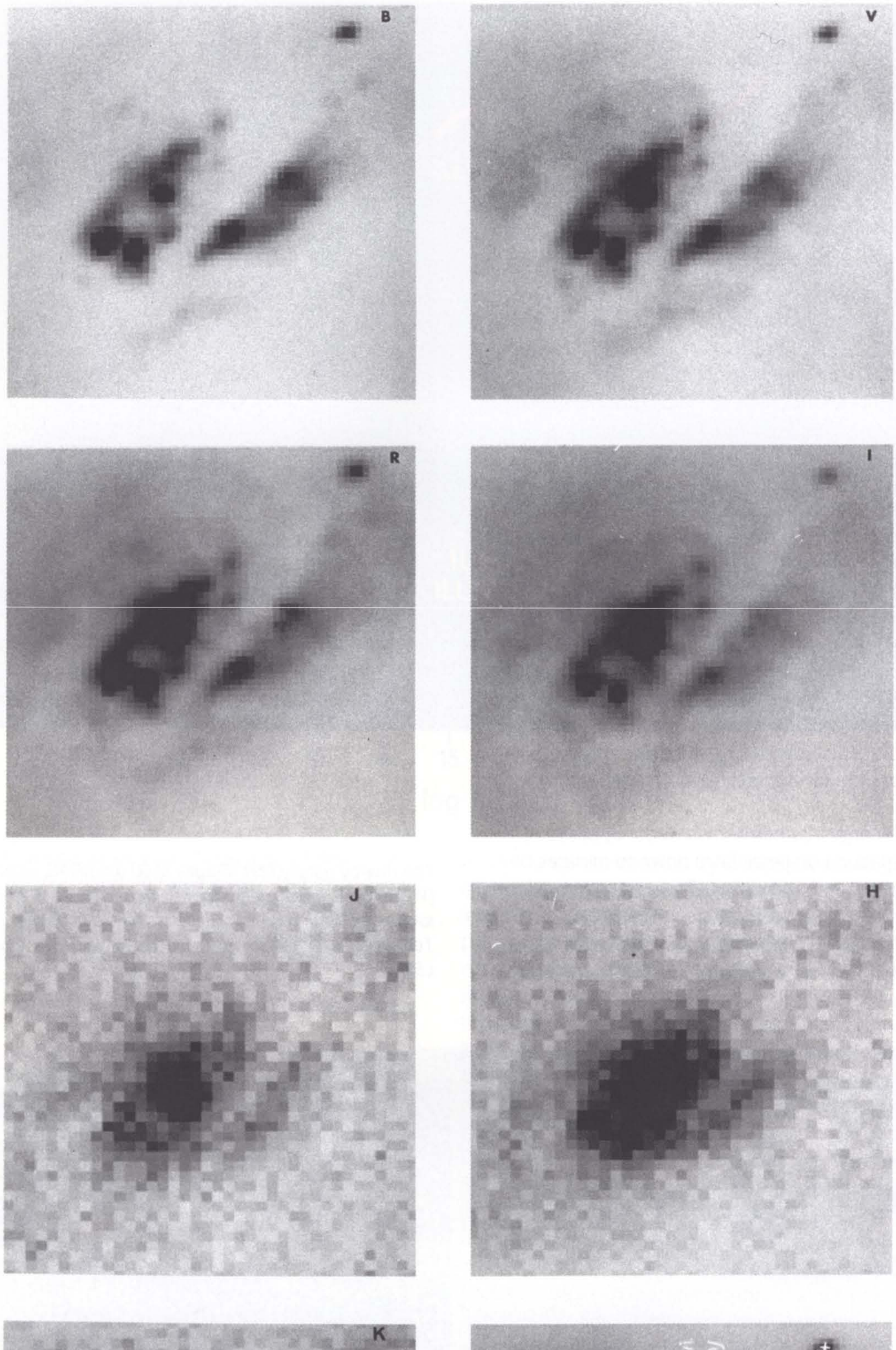
then be similar to that which constituted most other galaxies. The gas density within the cores of many clusters is so high that radiative cooling is important and an inflow takes place onto, and perhaps continuing to form, a central galaxy. Processes such as this are not discernible by ground-based techniques.

Clusters of galaxies also offer the possibility of a calibration-free determination of the expansion rate of the Universe (the Hubble Constant) and other cosmological parameters using the Sunyaev-Zeldovich effect. This is a characteristic change in the spectrum of the microwave background observed through a cluster and is produced by Compton scattering. Its amplitude is proportional to the density of intracluster gas along the line of sight. The X-ray surface brightness is, on the other hand, proportional to the square of the density. Microwave and submillimetre observations may then be combined with X-ray observations to yield a metric size for the cluster which, on comparison with its angular diameter, is converted to distance.

The most efficient energy sources known occur in *active galactic nuclei*. Variations on timescales down to minutes, enormous luminosities and massive outflows, often in the form of jets, provide a strong observational and theoretical challenge. It is generally considered that accretion onto a massive black hole is the basic underlying process. It can be

The nearby galaxy M31 images at 60 μm (IRAS, upper left); 50 cm (Westerbork Telescope, upper right); blue light (Palomar Observatory, lower left); and in the 21 cm line of atomic hydrogen (Westerbork Telescope, lower right). From Habing et al., 1984. Astrophys. J., 278, L59.

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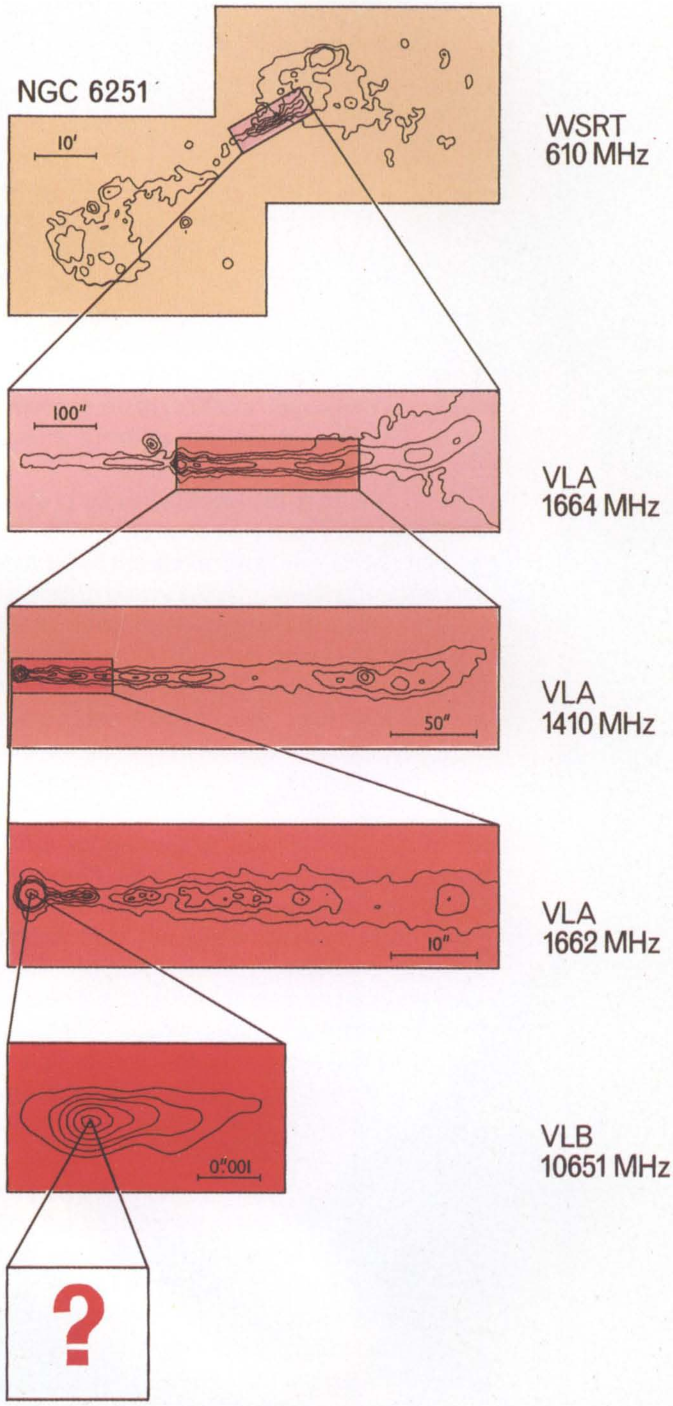
more than thirty times more efficient in the conversion of rest-mass to energy than is nuclear fusion. Understanding accretion and black holes is of primary importance both for astronomy and for testing the laws of physics under extreme conditions.

Most active nuclei do not confine their luminosity to any one waveband, but emit roughly equal amounts to all decades of the electromagnetic spectrum up to about 1 MeV. Spectral data is currently extremely limited in the far-infrared and X-ray wavebands. The hardest radiations are probably emitted from regions deepest in the potential well. The soft gamma-ray waveband has yet to be fully opened up, and offers the possibility of monitoring a large fraction of the bolometric flux from these objects, and of studying transrelativistic plasmas and nuclear processes.

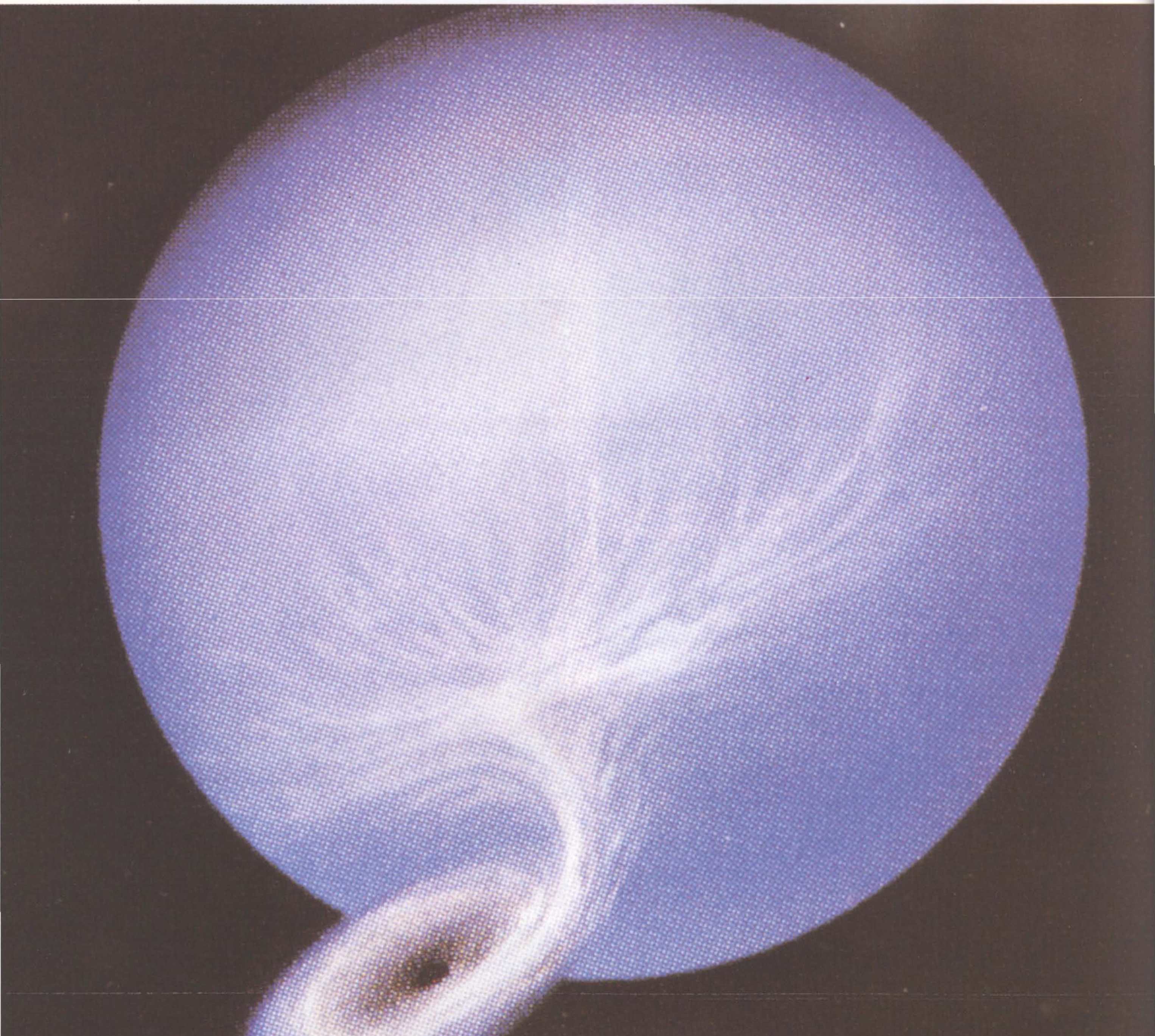
Observations of the evolution of active galaxies, which is already apparent although poorly understood, in QSOs should indicate how these regions are formed and grow. The fuelling of active nuclei and outflows are evident from optical and ultraviolet spectroscopy. Superluminal motions, attributed to relativistic outflows, are found in some nuclei. The predominance of jet structures on all scales from parsecs to megaparsecs in many objects demonstrates that a basic mechanism is operating in which a large fraction of the power is converted into kinetic energy. This could be due to rotation either of the accreting matter or of the central mass.

Space interferometry can resolve structures on scales ranging from milli- to micro-arcseconds at frequencies from the radio to the optical. This is particularly well-suited to the study of active galactic nuclei, which contain structure over a range of comparable scales. The emission from active nuclei and jets implies that efficient particle acceleration to relativistic energies is occurring. This is an extremely widespread process that cannot be studied in the laboratory. Our knowledge of plasmas under the extreme conditions common elsewhere in the Universe is still very limited.



The Seyfert 1 nucleus in the galaxy NGC 1365 imaged with a CCD from 0.4 μm (B) to 0.9 μm (I), and from 1.2 μm to 2.2 μm using the Anglo-Australian Telescope Infra-Red System. Note that the Seyfert nucleus is particularly red compared with the surrounding HII regions. (Courtesy of M.J. Ward.)

Montage showing the jet and counterjet of NGC 6251 over a wide range of angular scales. From the Westerbork Synthesis Rad'o Telescope (WSRT); the Very Large Array (VLA): and very long baseline (VLB) observations: Bridle & Perley, 1984. Ann. Rev. Astr. Astrophys., 22. The radio lobes extend about 1 Mpc from the central source; a distance exceeding that between ourselves and the nearest large galaxy.



In most binary X-ray pulsar systems the companion of the neutron star is a blue supergiant star, some 10 to 30 times more massive than the sun. Matter from the atmosphere of this star is captured in the super-strong gravitational field of the neutron star. The matter flows to the neutron star through a disk which, in its inner parts has a temperature of about 10^7 to 10^8K. The X-ray emission arises from the inner parts of the disk and from the surface of the neutron star. In the systems of Cygnus X-1 and LMC X-3, in which the compact star is thought to be a black hole, the X-ray emission arises only from the disk.

8. Galactic Astronomy from Space in the 1990's

E.P.J. van den Heuvel

Galactic astronomy covers a large range of astrophysical problem areas. Chief amongst these are: the formation and evolution of stars and planets, the physics of compact stellar remnants, the structure and dynamics of the interstellar medium, the origin of the heavy elements, the dynamic and chemical evolution of stellar populations, the origin of cosmic rays, and the nature of the galactic centre.

A key role in galactic astronomy is played by the supernova phenomenon, which interconnects many of the above-mentioned problem areas. The supernova also leads to the formation of compact objects: neutron stars and black holes. These present many fundamental physical problems ranging from the generation of super-strong magnetic fields and of high-energy electromagnetic radiations (X- and gamma-rays), to tests of the fundamental laws of nature, for example: the existence of gravitational waves, demonstrated by the orbital decay of the binary radio pulsar PSR 1913+16. For all of the above-mentioned problem areas, the use of space instrumentation is essential.

8.1 Introduction

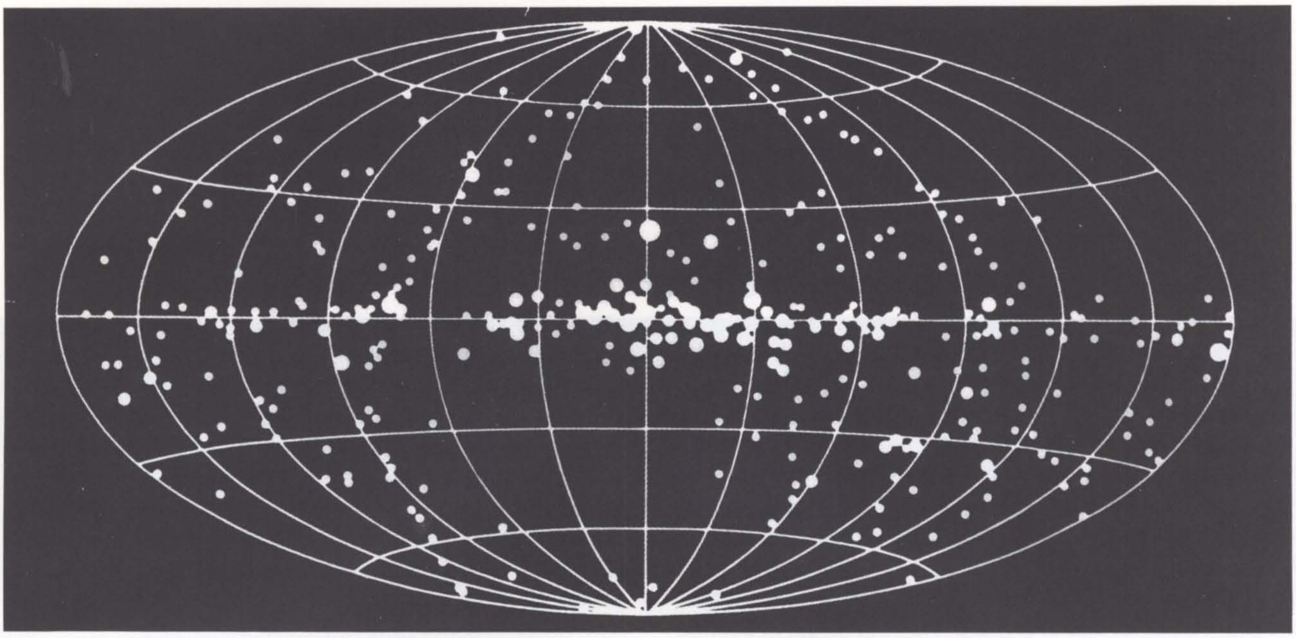
Important objects and physical processes of galactic astronomy can often be detected only by their emission of electromagnetic radiation outside the optical and radio wavelength bands. Without exaggeration it can be said that, in the past decade, space research has uncovered an entirely new 'galactic astronomy', the existence of which had never been suspected before. (In this respect our times resemble the first decades of the 17th century, when the invention of the telescope led to Galileo's discoveries of Jupiter moons, lunar craters, sunspots and thousands of new stars.)

Starting with the discoveries of the UHURU satellite, *X-ray astronomy* has become a major branch of galactic research. It showed us the existence of very strong and compact X-ray sources in binary systems, leading among other things, to the first accurate measurements of masses and magnetic field strengths of neutron stars, and to the identification of two prime black-hole candidates, Cygnus X-1 and LMC X-3. It furthermore revealed the emission of X-rays from a large variety of objects, such as supernova remnants, cataclysmic variables, globular clusters and the coronas of normal stars.

Ultraviolet astronomy, with the pioneering Copernicus and IUE spacecraft, led to the discovery of interstellar molecular hydrogen (H_2) and the hot interstellar medium and the hot galactic halo gas, heated by many overlapping supernova shock waves. It has also revealed the existence of large-scale stellar-wind mass loss from massive and luminous O- and B-type stars. The very large mass-loss rates of these stars – up to several times 10^{-5} solar masses (ten Earth masses) per year – have led to a revolutionary revision of our knowledge of the structure and evolution of the most massive stars.

Infrared astronomy, pioneered with IRAS, revealed for the first time the existence of at least two 'planetary' systems outside our own, surrounding the stars Wega and Formalhaut. It identified a large variety of entirely new phenomena, e.g. 'interstellar cirrus', and the evidence for enormous episodic mass ejection from red supergiant stars such as Betelgeuse, which lost some three solar masses in the last 10^5 years, leaving a clearly observable track in the constellation Orion. It also provided revolutionary new material on star formation and on planetary nebulae, the latest stages of the evolution of low-mass stars.

Finally, the COS-B satellite discovered the existence of a diffuse *gamma-ray emission* from the band of the Milky Way, and of several dozens of discrete galactic gamma-ray sources. The former is presumably due to the interaction of cosmic rays with



interstellar clouds; the nature of the discrete sources is still largely unknown, only two of them having been identified with well-known objects: the Crab and Vela pulsars. Another prime discovery of gamma-ray astronomy is the class of gamma-ray burst sources so far entirely unidentified, but suspected to be related to magnetised neutron stars.

The above-mentioned highlights show that, in the past decade, space research has become one of the major branches of galactic research. It is not only supplementary to ground-based astronomy, but is in itself of crucial importance to our understanding in most areas of galactic astronomy.

8.2 Boundary Conditions for the Selection of Missions for the 1990s

After the exploratory stages of the last decade, the time has now arrived for long-lived observatory-type missions, especially in the X-ray and UV wavelength ranges of the spectrum. The overwhelming number of applications for observing time for the IUE and EXOSAT spacecraft demonstrate the great need in the European astronomical community for missions of this type.

Supplementary to these big missions, there is also a need for exploratory missions in those wavelength ranges where exploration has just started. This is especially true for the gamma-ray, infrared and submillimetre ranges of the spectrum. In this respect, the ISO mission will be of great value. Also, for a later stage, beyond the year 2000, technological developments are expected to allow the deployment of optical and radio-astronomy missions in space (such as VLBI and Quasat) leading to an enormous gain in spatial resolution. Study of such missions should be further pursued, as these are expected to have a major impact on galactic research. They affect almost every branch of galactic astronomy, ranging from the search for planets around other stars to direct distance (parallax) and proper-motion measurements of stars throughout the entire galaxy.

An analysis of past astronomical discoveries has shown that, in general, the requirement for reaching a major scientific breakthrough is: at least one order of magnitude increase in: (i) sensitivity, or (ii) spatial resolutions, or (iii) spectral resolution, or (iv) time resolution or (v) number of objects studied (of a certain category). With these boundary conditions in mind, we will discuss the major areas of galactic astronomy and how these can be best served by planned and proposed European space projects in the 1990s.

8.3 Key Areas of Galactic Research and the European Space Programme in the 1990s

The key problem areas of galactic astronomy can be subdivided into a number of functional categories. These and their requirements in terms of space research are discussed below.

8.3.1 Highly Energetic Phenomena

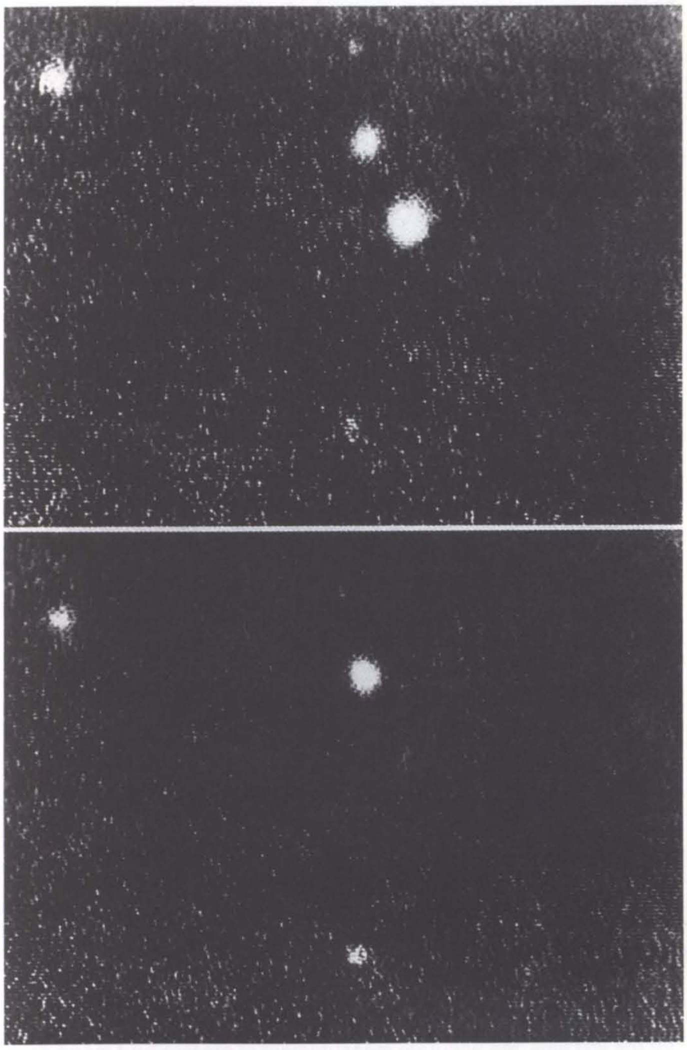
Supernovae, pulsars and cosmic rays
So-called Type-II supernovae mark the deaths of the most massive stars in the disks of spiral galaxies. They represent the final core collapse of such stars, leading to the formation of neutron stars or, much more rarely, black holes. The other type of supernovae, called Type-I, are believed to originate from stars of somewhat lower mass – presumably 4 to 8 solar masses – with degenerate carbon cores, and may not leave any compact remnant. Supernovae are believed to be responsible for the synthesis of heavy elements, and thus play a crucial role in the chemical evolution of galaxies and, ultimately, in the origin of stars, planets and life.

The process of core collapse releases 10^{53} erg, roughly equivalent to the total annihilation of 10% of the rest mass of the Sun. Most of this energy is lost in the form of energetic neutrinos – and only about 1% -10^{51} erg – becomes visible in the supernova explosion and the ejection of the supernova shell.

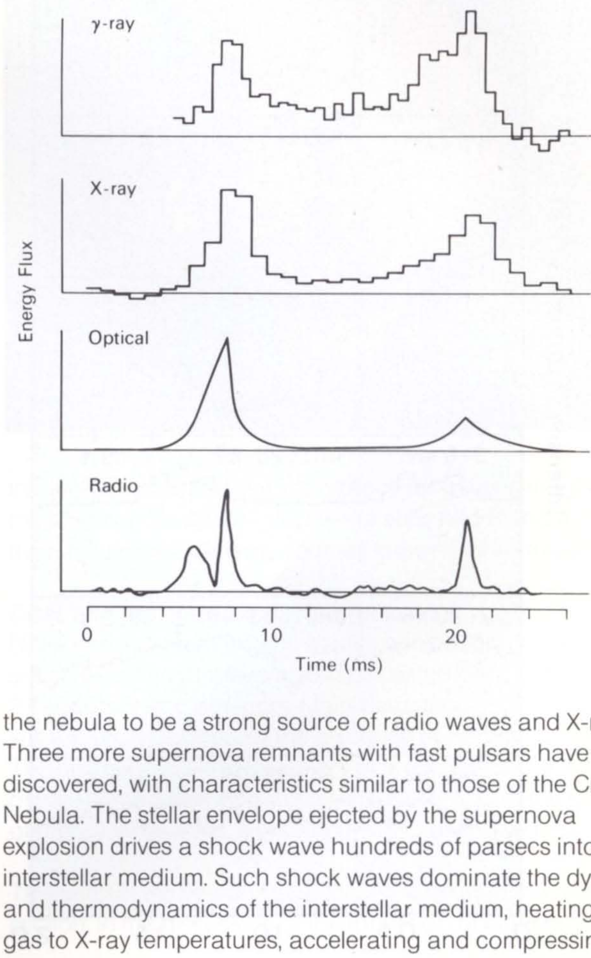
The neutron stars left behind by Type-II supernova explosions appear to be rapidly rotating, as a consequence of conservation of initial angular momentum. Their magnetic

The X-ray sky as seen by the UHURU-satellite, plotted in galactic coordinates. Only the strongest sources (10^{29} to 10^{31} watts, corresponding to 10^3 to 10^5 times the total luminosity of the sun) are plotted. One notices the strong concentration of sources along the band of the Milky Way, which is the equator of the coordinate system, and also towards the galactic centre. Most of the sources are neutron stars in close double star systems. Some sources are supernova remnants of black holes in double stars.
←

The pulsar in the Crab nebula, which was discovered in 1968, is a star which flashes on and off 30 times a second. On the upper photograph the pulsar – which is the lower component of the 'double star' – is on, in the lower photograph, taken 0.01 second later, it is off. Pulsars are rapidly rotating neutron stars, with a magnetic field some 10^{12} times stronger than that of the Earth.
(Photograph Courtesy Lick Observatory).



Pulse-graphs of the Crab-nebula pulsar in four energy bands, shows the importance of observations at all possible wavelength bands. The pulsar emits most of its energy in the X- and gamma-ray wavelength-band.

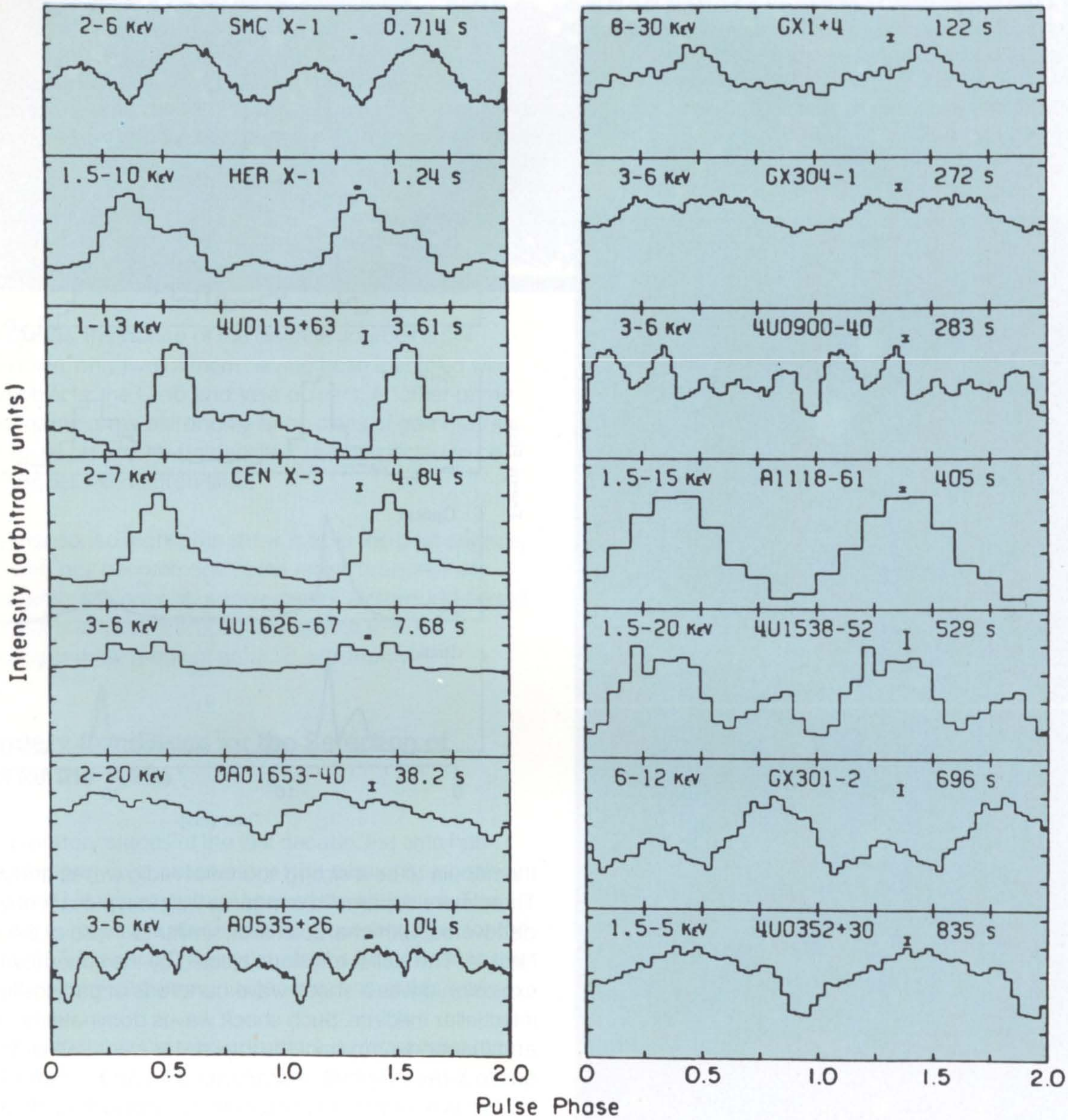


fields typically have a strength of order 10^{12} G. The rapid rotation of these fields produces very strong electric fields, leading to the acceleration of particles to ultra-high energies. The beamed radiation emitted by these particles, in combination with the rapid rotation, produces the pulsed character of the observed radiations from the pulsar. Over 400 radio pulsars have been identified. The pulsar in the Crab Nebula, resulting from supernova 1054, has been observed to emit pulsed radiation in all wavelength ranges from radio waves to gamma rays. Particle acceleration in the Crab Nebula due to the pulsar is observed to be taking place and causes the nebula to be a strong source of radio waves and X-rays. Three more supernova remnants with fast pulsars have been discovered, with characteristics similar to those of the Crab Nebula. The stellar envelope ejected by the supernova explosion drives a shock wave hundreds of parsecs into the interstellar medium. Such shock waves dominate the dynamics and thermodynamics of the interstellar medium, heating the gas to X-ray temperatures, accelerating and compressing interstellar clouds and presumably initiating the collapse of molecular clouds, leading to star formation.

The scattering and acceleration of fast particles by turbulence in the post-shock plasma can account for both the energy spectrum and the flux of galactic cosmic rays observed at the Earth. It can also account for the diffuse gamma-ray background of the Milky Way.

Binary Systems, and the physics of accretion and of relativistic jets

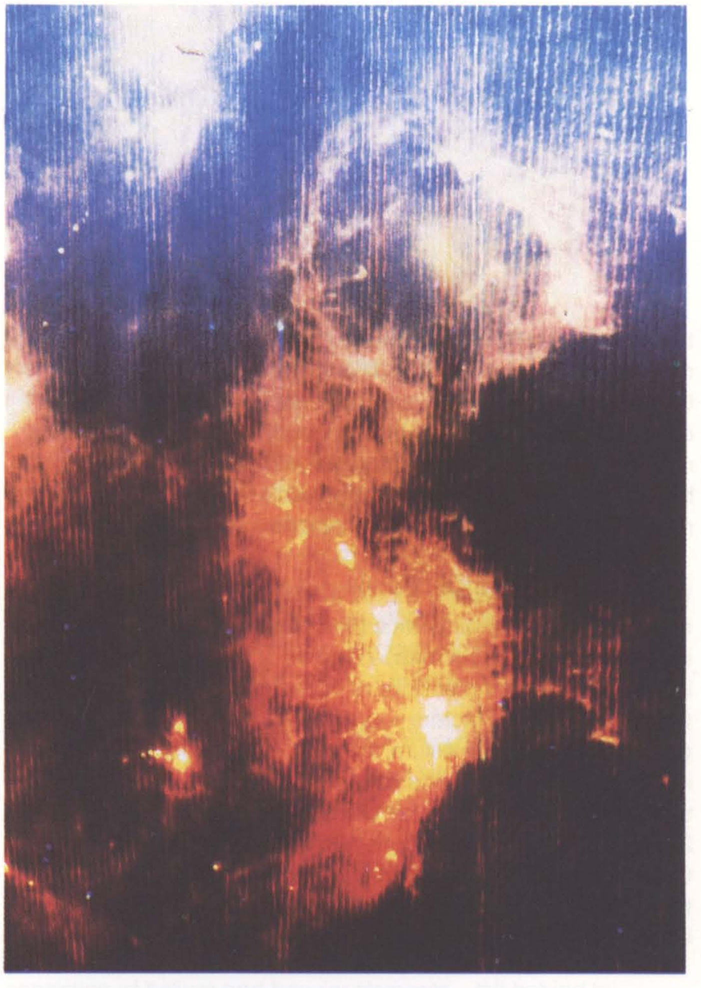
The majority of stars are found in binary systems. Many binaries are sufficiently close to allow the two components to interact strongly with one another and to influence each other's evolution. These interactions produce observable effects which



Pulse profiles of 14 binary X-ray pulsars. These systems have allowed for the first time, the accurate measurement of masses and magnetic field strengths of neutron stars.

allow one to derive basic properties of each component which could never be determined for single stars. A prime example is formed by the category of the binary X-ray sources, one of the most important discoveries in astrophysics of the 1970s. The pulsating binary sources allow one to determine masses and magnetic-field strengths of the neutron stars that produce the pulsed X-ray radiation by capturing gas from the atmospheres of their normal companion stars. The inflowing matter in most cases forms an accretion disk, having a temperature of the order of tens of millions of degrees K.

The process of accretion, which feeds these binary X-ray sources, is the most efficient energy generation process so far discovered in the Universe. In it, more than 10% of the rest mass of the accreted matter is converted into high-energy radiation. This efficiency exceeds that of hydrogen-fusion by a factor 14.



False-colour image of sky around the constellation Orion produced from data from the Infrared Astronomical Satellite (IRAS), Courtesy NASA.

Two binary X-ray sources, Cygnus X-1 and LMC X-3, have provided strong evidence for the existence of stellar-mass black holes. Isolated black holes cannot be detected, but a black hole in a binary that is accreting gas from a companion star can become observable by the X-ray emission from the inner parts of its accretion disk. Analysis of the orbits of Cygnus X-1 and LMC X-3 shows that both of them contain compact objects with a mass of about 10 solar masses. In the absence of any plausible alternative interpretation, these objects are the strongest black-hole candidates known to date.

A further search for black-hole candidates and the careful study of their properties is one of the greatest challenges of X-ray astronomy in the 1990s. X-ray missions of high sensitivity, and high time and spatial resolution are absolutely essential for this.

Other major categories of binary X-ray sources are the X-ray burst sources and the cataclysmic variables. The burst sources belong to an old stellar population and are concentrated in globular clusters and near the galactic centre. They emit violent bursts of X-ray radiation with a duration of 10–100 s and an X-ray luminosity equivalent to one million solar luminosities. The bursts are ascribed to thermonuclear fusion on the surface of the neutron star.

In the cataclysmic variables, the accreting object is a white-dwarf star. These systems are particularly suitable for the study of the properties of accretion disks. The latter emit most of their radiation in the UV, EUV and X-ray parts of the spectrum.

Several of the galactic binary X-ray sources are observed to produce collimated jets of relativistic particles, in many respects similar to those observed in active galactic nucleii and quasars. The prime example is the peculiar massive X-ray binary SS 433, which emits about one Earth mass per year in two oppositely directed narrow jets of gas with a quarter of the velocity of light. The jets, as well as the large accretion disk from which they originate, are observed to be precessing with a period of 164 days. Another X-ray source with relativistic jets is Scorpius X-1, a low-mass X-ray binary which is the strongest X-ray source in the sky.

The many similarities between these compact galactic X-ray sources and the much larger extragalactic nuclear sources has led to the idea that the underlying physical mechanisms must be basically similar, i.e. the inflow of gas, towards a compact object, through an accretion disk. The formation of the jets is clearly intimately related to the physics of the accretion disks. The accreting galactic X-ray sources offer the advantage that these processes can be quantitatively studied in much more detail than would ever be possible in active galactic nuclei and quasars. The study of accreting binary X-ray sources is therefore of fundamental importance for gaining insight into the physical processes in active galactic nuclei and quasars, the most powerful energy sources known in the Universe.

Disks and jets associated with protostars

Disks and jets appear to be a quite general phenomenon also in entirely different areas of galactic astronomy, notably among T Tauri stars and other pre-Main-Sequence objects. Here the jets are often outlined by the presence of Herbig-Haro objects. The accretion disks involved are of a size comparable with that of the solar system. Apparently, therefore, also in the formation of planetary systems, disks and jets are of crucial importance.

This subject will be considered in more detail in the next section, in the discussion of the formation of planetary systems.

Requirements

The problems described in this section require general-purpose facilities with high spatial, temporal and spectral resolution in the X-ray and UV parts of the spectrum. In the X-ray region, AXAF will provide the necessary high spatial resolution and XMM appears an ideal supplement for providing sensitivity, timing and spectral capabilities. For the UV/EUV parts of the spectrum Columbus is very well suited.

8.3.2 The Interstellar Medium and the Formation of Stars and Planetary Systems

Interstellar matter and star formation

The Copernicus ultraviolet satellite in 1973 discovered the presence of H_2 in the interstellar medium, by measurement of the interstellar ultraviolet absorption lines of H_2 in the spectra of distant stars. Roughly half of all interstellar hydrogen in the Galaxy (5 billion solar masses) appears to be H_2, while the other half is H I. The far-ultraviolet instruments of the Columbus mission will permit the extension of the study of H_2 to much larger distances and will make it possible to generalise the results of the rather limited observations gathered so far.

With the Copernicus and IUE ultraviolet spectroscopic missions, many elements were discovered to be depleted in interstellar space (from measurements of the strengths of interstellar lines in the spectra of distant stars). These depletions by large factors suggest that many elements – primarily silicon, magnesium, and iron – are largely locked up in interstellar grains. This is confirmed by the detection of strong interstellar absorption bands in the infrared, at 10 and 20 μm, characteristic of magnesium silicates. The ST and the Columbus mission, with its far-UV spectrograph, will extend these studies to all the strong spectral lines of the abundant interstellar elements.

Another discovery of the Copernicus mission was the hot interstellar medium ($T \sim 2-5 \times 10^5$ K) characterised by highly ionised oxygen (O VI). Observations with the IUE spacecraft showed this hot gas to extend far into the galactic halo. With the much more sensitive instruments of Columbus, the spatial distribution of this gas can be accurately mapped to very large distances by measuring its absorption lines in the spectra of distant stars and galaxies.

Interstellar dust is an important component of the interstellar medium. Dust is formed as a result of cooling in the expanding shells ejected by red giant stars and novae. On the other hand, dust and many species of interstellar molecules are also abundantly present in star-formation regions, as is revealed by infrared observations, as well as by ground-based observations at radio and millimetre-wavelengths. The radiation of young and luminous stars – hidden inside the clouds – heats the dust which, in its turn, begins to radiate at infrared and submillimetre wavelengths. The radiation from these 'cocoon' stars is characteristic of the densest parts of the molecular clouds, which indicates that the hot stars responsible for the heating have just formed inside these clouds. Radio observations suggest that the most massive and luminous stars that have formed in the clouds ionise the parts of the clouds closest around them, producing ionisation shock fronts that compress the adjacent parts of the clouds, driving them to gravitational collapse and star formation. Associations of O- and B-stars and of T Tauri stars are expected to be formed in this way.

In addition to ground-based radio and millimetre observations, infrared and submillimetre observations from space are an essential means of precisely mapping these processes of star formation in the dense molecular clouds, and of deriving the precise physical conditions of temperature, density, velocities, chemical composition and gas to dust ratio of the clouds. Missions such as ISO, FIRST and SIRTF are of essential importance for this type of research.

The importance of X-ray and gamma-ray observations of the interstellar medium have already been summarised above.

As already mentioned, supernovae supply the energy for producing the hot intercloud medium. They are also thought to provide the first trigger for driving the denser and cooler (100 K) molecular cloud complexes towards collapse, leading to the formation of the first massive stars. These, in their turn, start the star formation processes outlined above. Whether this course of events does indeed occur as outlined above, can only be learned from measuring the precise physical conditions in the cool clouds and in the hot intercloud medium, as well as in supernova remnants. In addition to the IR and submillimetre observations from space, this also requires ultraviolet and X-ray spectroscopic observations of the hot components of the interstellar medium. For this, missions such as XMM and Columbus are required.

Formation of planetary systems: protostars, disks and jets
Formation of planetary systems is a direct byproduct of star formation. As mentioned above, very large accretion disks, and associated jets have recently been discovered around T Tauri stars and other pre-Main-Sequence objects, like Herbig Ae and Be stars. The cool and extended parts of the disks are observable only at far-infrared and submillimetre wavelengths, like the 'planetary' disks around the stars Wega and Formalhaut, discovered with IRAS. On the other hand, flaring activity at X-ray wavelengths is observed in many T Tauri stars, notably in the Orion Nebula cluster, and in Herbig Ae and Be stars. This flaring presumably originates in the inner parts of the disks, where differential rotation leads to winding up of magnetic field lines, resulting in the generation of very strong magnetic fields. When the field strengths exceed a certain critical value, presumably field-line reconnections occur, resulting in frequent flaring activity at X-ray, ultraviolet, optical and radio wavelengths. The flares resemble giant solar flares. In the early history of the solar system similar processes must have take place. Ultraviolet and X-ray spectroscopic studies of pre-Main-Sequence objects are necessary to derive the precise physical conditions in these hottest inner parts of their disks, and to study the mass ejection (presumably in directions perpendicular to the disks) associated with these phenomena.

It is exciting to realise that, by means of the above-described studies, it is becoming possible for the first time in history to study in detail the physical processes that led to the formation of our own planetary system, some 4.6 billion years ago. Ground-based observations are only of limited value here and very sensitive space-based facilities are absolutely essential, at all wavelength ranges from X-rays to the submillimetre band. This requires missions such as XMM, Columbus, ISO and FIRST, in addition to the US missions AXAF and SIRTF.

8.3.3 Stellar Activity and Mass Loss

Stellar activity, hot coronas and flares

X-ray observations with the Einstein Observatory have shown that nearly all types of stars have coronas with temperatures of the order of millions of degrees, implying the existence of magnetic fields, stellar winds and probably, in many cases, flaring activity. In 1974, the ANS spacecraft discovered enormous X-ray flares from so-called 'flare stars' (a class of stars characterised by gigantic optical and radio flares, and by the presence of large-scale star-spot activity).

Magnetic activity, often with a cyclic behaviour resembling the 11-year solar activity cycle, has been discovered by means of optical spectroscopic observations in a number of solar-type stars. This is suspected to be a general characteristic of stars with convective envelopes. Fundamental physical problems here are the generation of the stellar magnetic fields, the heating of their chromospheres and coronas, and the acceleration of particles to relativistic energies, during flaring outbursts. Such types of stellar activity are best studied by means of high-resolution spectroscopy in the X-ray and UV-parts of the spectrum, where most of the energy emission of the hot stellar chromospheres, coronas and flares is formed. (By analogy with solar flares the flares are also expected to emit a considerable quantity of gamma rays.) Measurement of strengths and widths of spectral lines will make it possible to derive the physical conditions of temperature, density and mean magnetic field strengths in these hot plasmas.

Stellar winds and mass loss

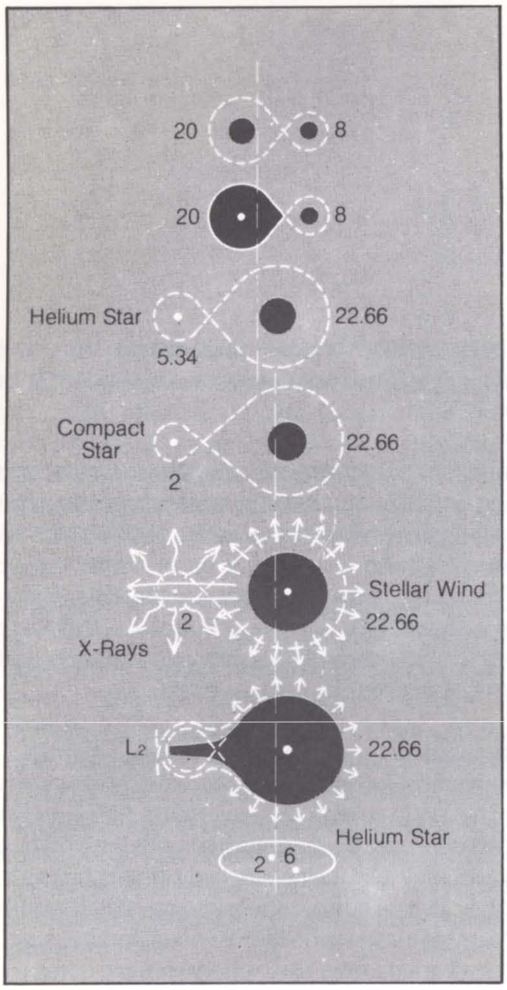
Ultraviolet observations by the Copernicus and IUE spacecraft, later supplemented by radio and infrared observations, have revealed the existence of very strong stellar winds in blue hot supergiant stars as well as in cool red giants and supergiants.

The most luminous O and B stars are observed to lose mass at rates up to several times 10^{-5} solar masses per year, at velocities of the order of 2000–3000 km/s. In this way, they may lose as much as three quarters of their mass during their lifetime.

Time variations of ultraviolet line profiles show that these winds are highly unstable and that the mass loss apparently takes place in the form of an irregular series of shells. The driving mechanism of these strong winds is not known. It is probably related to the very large luminosities of the stars. The winds themselves blow large 'interstellar bubbles' – shocked regions of interstellar gas resembling supernova remnants and containing a similar total amount of energy.

Infrared observations with IRAS have shown that red supergiants, like Betelgeuse, also have very large mass loss rates, again up to several solar masses in 10^5 years. These combined observations suggest that both red and blue supergiants may lose their entire hydrogen-rich envelopes during their lifetime, turning them into so-called 'Wolf-Rayet stars'. Many of these extremely luminous and hot stars do not contain hydrogen and most probably are the cores – consisting of helium and heavier elements – left behind by evolving stars that were initially more massive than 30 solar masses. The Wolf-Rayet stars have the strongest winds of all stars, for reasons that are so far unknown.

The Exosat CMA image of RCW 86.



The evolution of a massive, close, binary-star system as postulated by E.P.J. van den Heuvel (Univ. of Amsterdam).

From top to bottom:

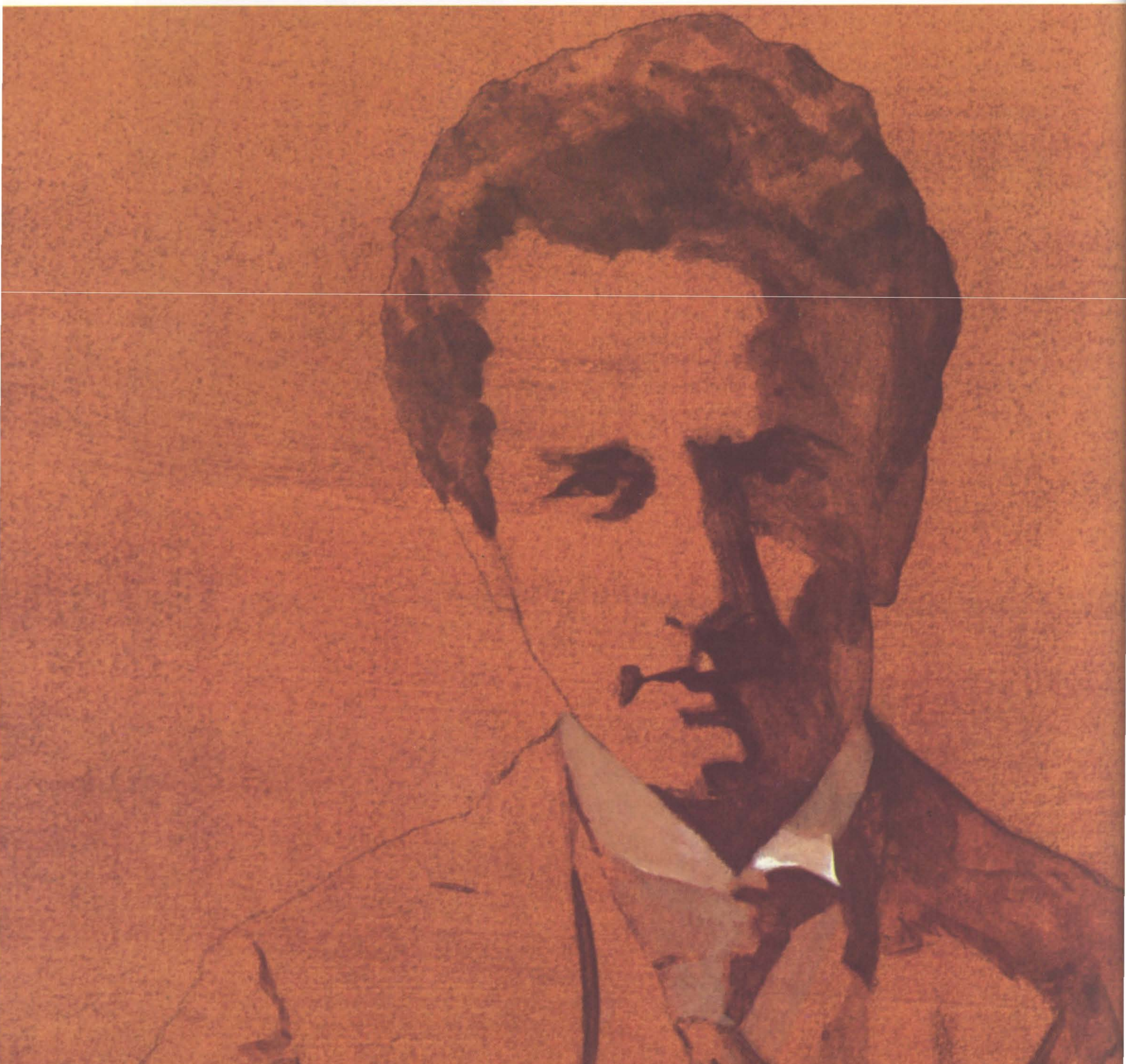
- *Start with two stars (20 $M_\odot$* and 8 $M_\odot$) in a binary system with an orbital period of 4.7 days both burning hydrogen.*
After 6.17 million years stellar material starts to flow from the larger to the smaller.
- *After 6.20 million years the first stage of mass exchange is complete, the now smaller star burns helium and the orbital period has changed to 10.86 days.*
- *After 6.76 million years the helium star has exploded as a supernova leaving behind a compact neutron star; the system now has a period of 12.63 days.*
- *After 10.41 million years the larger star becomes a super giant and the outflowing stellar wind falls onto its compact companion which becomes a powerful X-ray source.*
- *After 10.45 million years, material flows from the massive star to the compact one, extinguishing the X-ray source and the combined system loses mass to space.*
- *After 10.47 million years the massive star has reduced to 6 $M_\odot$ and helium burning starts. After 11 million years the new helium star explodes as a supernova to leave behind a young compact star. If this new compact star is heavy (approx. 3 $M_\odot$) the pair survive together; if light (approx. 1 $M_\odot$) the two stars will go their separate ways.*

* *$M_\odot$: solar mass, 1 $M_\odot = 2 \times 10^{33}$ grams.*

Winds from hot stars in the Large Magellanic Cloud suggest a rather strong dependence of mass loss rates on the initial heavy-element abundance. This may be an important clue to the driving mechanism of winds of early-type stars. The existing UV spectroscopic spacecraft are, however, unable to reach more than the few brightest stars of the Large Magellanic Cloud, and none in the Small Cloud, so that this hypothesis can not yet be tested. A sensitive UV spectroscopic mission like Columbus is urgently required to enable this subject to be pursued further and to extend the research to stars in other nearby galaxies.

Such a mission is also required for the study of other basic aspects of the stellar-wind problem, such as: (i) How do the winds fluctuate? (ii) Is fluctuation an essential characteristic of all winds of early-type stars? (iii) Do all stars with strong winds have hot coronas? The last question also requires a high-resolution X-ray spectroscopic mission like XMM.

In addition, the precise measurements and calibration of the total rates of mass loss from all types of stars require infrared and submillimetre observations (to measure the free-free emission from the winds). For this ISO, FIRST (and the US mission SIRTF) are required.



Albert Einstein as a young man. His most important works, the Special Theory of Relativity and the General Theory of Relativity, were published during the early years of his career.

Courtesy TRW.

9. Space Experiments in Relativity and Gravitation

I.W. Roxburgh

Although gravity is the weakest of the known forces of nature, it dominates and controls the large-scale dynamics of the Universe and macroscopic astrophysical bodies within it. The areas of application are almost (perhaps in fact) limitless – the expansion of the Universe, the structure of stars, galaxies, condensed matter, collapsed objects, gravitational waves, etc., etc. The areas of applications are vast, yet the empirical basis of the theory of gravity is weak.

9.1 Introduction

The theory of gravitation is fundamental to physics and to astronomy, and space experiments offer the possibility of providing experimental evidence to test our theories and extend our understanding.

Such experiments are designed to push to the limits measurements of the behaviour of clocks, light signals and test bodies in the gravitational field of other bodies (principally the Sun) and to search for gravitational waves which cause a fluctuation in the distance between the Earth and distant bodies.

The discovery of gravitational waves, the frame-dragging effect of spinning bodies and higher order post-Newtonian effects on clocks, light rays and test bodies will all greatly extend our knowledge of the theory of gravitation. If the solar quadropole moment can be measured to sufficient accuracy, it will improve our tests of post-Newtonian gravity as well as provide valuable information on the solar interior. It is important to look for effects such as periodic variations in planetary orbits predicted by non-metric theories and to recognise that new effects may be encountered at the $1\frac{1}{2}$ post-Newtonian order.

General Relativity and other theories of gravity predict the emission of gravitation radiation by moving sources. Such waves passing through the solar system can be detected by a characteristic fluctuation in the Earth–satellite distance. The detection and the polarisation of such waves would mark a breakthrough in both gravitational physics and astrophysics.

The tools of the space experiments in gravitational physics are clocks and range and range-rate data. Non-gravitational perturbations on orbiting bodies must be either negligible or corrected for. This leads to the following requirements:

1) deep-space missions with two-frequency tracking (essential)
2) on-board clocks (highly desirable)
3) space antennas for receiving ranging data (highly desirable)
4) drag-free or planetary orbiters/landers (for some experiments)

In general, we expect gravitational experiments to be part of a larger mission, for example:

a) Mercury orbiter
b) missions to the outer planets
c) solar probe.

(Courtesy NASA)

Within the European community, expertise in analysing such data has been developed either in conjunction with NASA, or independently as part of studies on earlier missions. Were ESA to include experiments at the limit of sensitivity as part of other space missions, this could lead to a significant – even dramatic – advance in our understanding of gravity and of astrophysics.

9.2 Some Historical Considerations

Newton's theory of gravity, whilst an intellectual triumph of the first order, was based on both the patiently-acquired empirical data of Tycho Brahe and Kepler, and on the pioneering work of Galileo. The resulting theory successfully explained an enormous range of phenomena and, in the hands of successive generations of mathematical scientists such as Laplace, was able to account for almost all the observed phenomena in the solar system. The theory had both an empirical base and a wide range of successful predictions to support the theory. It remains highly successful and capable of 'explaining the phenomena'.

It is not 'correct'. The theory most widely accepted and used today is Einstein's General Theory of Relativity. This theory has neither the strong empirical base, nor the range of successful predictions to justify the widespread confidence in and application of the theory.

The need to modify Newton's theory was perceived in the 19th century following the discovery of the anomalous advance of the perihelion of Mercury's orbit, the development of Maxwell's theory of electromagnetism and the discovery of special relativity. The need to develop a relativistic theory of gravitation and dynamics was clearly seen by Poincaré and, indeed, in his 1905 and 1906 papers on special relativity he put forward a relativistic extension of Newton's theory. The following decade witnessed a number of attempts to develop a relativistic theory of gravitation, culminating in Einstein's General Theory of Relativity in 1915.

Einstein's theory – as do others – necessarily reduces to Newton's theory in conditions of slow motion and weak fields. It successfully explained the motion of Mercury's perihelion and was widely accepted following Eddington's 1919 experiment, which confirmed the predicted deflection of light as it passed close to the Sun. General Relativity, and a host of rival theories, also predicted the gravitational red shift, subsequently confirmed by the Pound-Rebka experiment and more recently by the Harvard-Smithsonian hydrogen-maser rocket flight. In 1964 it was pointed out by Shapiro that a further prediction of the time delay in signals passing close to the Sun could also be tested, and this has indeed been verified by subsequent radar-ranging experiments to satellites and planets in the solar system.

Following the success of Einstein's theory in explaining these few experiments, the theory became widely accepted and its consequences evaluated in a range of conditions far beyond those in which it had been tested. Other theories, some of which were equally successful in 'explaining the phenomena' were ignored or forgotten and theoretical speculation far outstripped experimental investigation. This was an unhealthy development – the normal pattern of evolution of science is that of an interplay between theory and experiment, sometimes theory leading, to be destroyed by experiment, sometimes experiment leading, providing an empirical base for future theories.

A substantial change in philosophy came in the late 1950s and early 1960s. Challenging alternative theories were developed, new discoveries in astrophysics stimulated research in gravitation, and space opened up the possibility of new and more accurate experiments to probe our understanding. But theory still races far ahead of experiment and a plethora of alternative theories has been developed. This in turn has contributed to our understanding of the significance of experimental verification, but the effects predicted are so difficult to measure that progress is dependent on more accurate observations than have yet been made.

9.3 General Relativity

General Relativity is a 'metric theory' in that the behaviours of clocks, bodies and radiation are governed by the quadratic Riemannian metric

$$ds^2 = g_{ij}\, dx^i\, dx^j$$

where the metric tensor g_{ij} is determined by the position of sources through the field equations

$$R_{ij} - \frac{1}{2} g_{ij} R = -\kappa T_{ij}$$

where $\kappa = 8\,\pi G/c^4$ is a constant. The laws of physics for non-gravitational interactions have the same form in local Lorentz frames as in the flat space and time of special relativity.

For the spherically symmetric empty space surrounding a spherical mass, the metric can be expressed as

$$ds^2 = \frac{(1 - GM/2\,rc^2)^2}{(1 + GM/2\,rc^2)^2}\, dt^2 - \frac{1}{c^2}(1 + GM/2\,rc^2)^2$$

$$(dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2)$$

Expanding this metric in powers of GM/rc^2, we can write

$$ds^2 = \left(1 - \frac{2\,GM}{rc^2} + 2\beta \left(\frac{GM}{rc^2}\right)^2 + \ldots\right) dt^2 - \frac{1}{c^2}$$

$$\left(1 + 2\gamma \frac{GM}{rc^2} + \ldots\right) \quad (dr^2 + r^2 d\theta^2 + r^2 \sin \phi d\phi^2)$$

where $\beta = \gamma = 1$ for General Relativity, but differ from unity in some other theories.

The predictions of this metric have been studied by several experimenters, as has the constancy in time of the gravitational constant G. The value of β is linked to the value of the solar quadropole moment J_2, which also produces an advance of a planet's perihelion, and the current limits are

$$\gamma = 1.000 \pm 0.002 \qquad \beta = 1.06 \pm 0.12$$

$$J_2 = (-1.4 \pm 1.5)10^{-6} \quad G/G = (0.2 \pm 0.4)10^{-11}\, y^{-1}.$$

Thus at this level the predictions of General Relativity are confirmed.

Moreover, the weak-equivalence principle, the equivalence of gravitational and inertial mass, has been verified in the laboratory by the Etvos experiment and by lunar laser ranging.

9.4 Other Theories of Gravity

Other theories of gravity differ from General Relativity in two fundamental ways:

a) *Non-metric theories.* In these theories the quadratic metric hypothesis is abandoned and replaced by some other assertions. These could be a metric affine theory, or a quartic metric, or two metrics or...
b) *Metric theories* in which the field equations that determine the g_{ij} in terms of the sources differ from those of General Relativity.

In non-metric theories, phenomena may be predicted that are absent in metric theories. One such is a periodic perturbation in the orbits of planets or satellites. Another is that the 'constant of gravity' G may, in fact, be time varying the argument here being that, if G is determined by the global distribution of matter in the Universe, we might expect it to vary as the Universe expands. Another possibility is orientation-dependent effects, either because of a preferred direction in space or because of the solar system's motion relative to the global frame of the Universe.

All metric theories, on the other hand, can be compressed into the Parameterised Post-Newtonian (PPN) approximation and the result of this class of theories tested against existing experiments to the order $1/c^4$. This is the thrust of most of the recent analysis and the claim that General Relativity is substantiated to this accuracy is based on such work. However, even here care should be exercised; it is assumed that the metric g_{ij} can be expanded as a power series in the gravitational potentials (e.g. GM/cr^2), the possibility of fractional powers is ignored.

9.5 Future Experiments

9.5.1 Effect of Spinning Bodies

Within General Relativity (and other metric theories), one of the most important problems is that of the field of a non-spherical rotating mass, the so-called 'frame-dragging effect'. A spinning mass destroys symmetry and introduces a non-conservative contribution to the metric. The simplest example of this is that the time for a light signal to cover a closed path containing the spinning body is different for the two different ways round the closed path.

This frame-dragging effect on the motion of bodies will be studied by the Stanford experiment involving the placing of a gyroscope in orbit around the Earth and monitoring of the procession of its spin axis. Were these results to agree with the predictions of General Relativity, this would give confidence in applying the theory in various astrophysical situations. Were the results to disagree with General Relativity, this of course would be a major step in experimental physics.

This same frame-dragging effect can be studied by the propagation of light, or electromagnetic waves close to the rotating Sun. With a clock on board a satellite (say a Mercury orbiter), the one-way time delay could yield a measurable result due to the angular momentum of the Sun.

9.5.2 Solar Quadropole Moment

The orbits of test bodies or planets in the solar system are, of course, also influenced by any non-spherical gravitational field of the Sun. This quadropole (J_2) effect also causes an advance of perihelia, similar to, but different from, that produced by post-Newtonian gravity. Accurate tracking of a satellite on an eccentric orbit (Solar Probe or Mercury orbiter) could yield an accurate determination of J_2, and hence an accurate determination of the relativistic contribution to perihelion advance.

9.5.3 Non-linear effects

In this category are experiments designed to measure the effect of gravitational potentials on the rate of clocks to one order higher than has so far been achieved. This requires accurate two-frequency ranging to a very stable (hydrogen maser) clock that is close to the Sun. Such an experiment could be conducted on a satellite like the Solar Probe, which goes down to a few solar radii.

Such an experiment gives an independent measure of β. Within General Relativity and other metric theories this has the same value as that governing the perihelion advance. There is no *a priori* reason why this should be so. Were one to find that the second-order red shift gave a different value of β, this would be of great importance.

The bending of light and time-delay experiments are currently first-order, i.e. measure terms of order GM/rc^2, or V^2/c^2. The next highest order is not necessarily V^4/c^4, but one could find new effects at the level of V^3/c^3. The current experiments are approaching this accuracy and it is possible to push these by an extra order of magnitude to look for effects at this level.

Moreover, as has already been pointed out, non-metric theories can contain periodic effects on planetary orbits. Such effects, if they exist, need to be searched for both in existing data and at the highest level of accuracy that can be achieved. Similarly, bending of light and time-delay experiments are now approaching the level of accuracy at which preferred direction effects may be significant (if they exist). The motion of the solar system relative to the cosmological reference frame is of order $V/c \sim 10^{-3}$, so at the level of 1 in 10^3 orientation dependent effects could appear, provided such effects are looked for in the data analysis!

9.5.4 Gravitational Waves

Einstein showed over 60 years ago that gravitational waves should exist as 'ripples' in the metric g_{ij}. This prediction is, of course, true of a whole class of theories of gravitation where, by analogy with electromagnetic theory, we would expect moving sources (e.g. masses) to produce such radiation. Attempts to detect such radiation by ground-based experiments have so far proved unsuccessful.

Space experiments offer a different opportunity to search for such waves in fluctuations in the range and range-rate measurements between Earth and a distant satellite. A wave passing the Earth-satellite line produces a 'jiggle' in the metric, and hence propagation effects, which have a characteristic signature which facilitates detection. Since the expected magnitude of such waves is unknown, the requirement is for as accurate range and range-rate data as possible, two-frequency ranging, and preferably an orbiting antenna and an on-board clock.

The detection of such waves would be a landmark in the development of gravitational physics, and the first step to opening up a new area of astrophysical observations – the gravitational wave spectrum as opposed to the electro-magnetic wave spectrum.

But the detection of such waves is of intrinsic interest in further understanding the theory of gravity. General Relativity predicts two states of transverse polarisation differing by 45°; other theories of gravity predict up to six such states. Were two and only two states to be detected, this would be strong evidence in support of a theory (GR) in which the field is governed by an elementary particle of spin 2 and zero rest mass.

The possible sources of such gravitational radiation are many, and estimates of the wave amplitude uncertain. A stochastic background could exist as a result of the formation of black holes in the early stages of the Universe or from the Big-Bang itself. Were such a background to have $|\delta g| \sim 10^{-15}$ at about 10^{-3} Hz, it could be sufficient to close the Universe.

The formation of massive black holes could lead to detectable amplitudes and binary systems could also produce a flux of gravitational waves .

At present we are unable to predict with any confidence the strengths of any such waves passing through the solar system, but the successful discovery of such waves could be of immense significance for gravitational physics and for astrophysics.

9.5.5 Time Variation of the Gravitational Constant

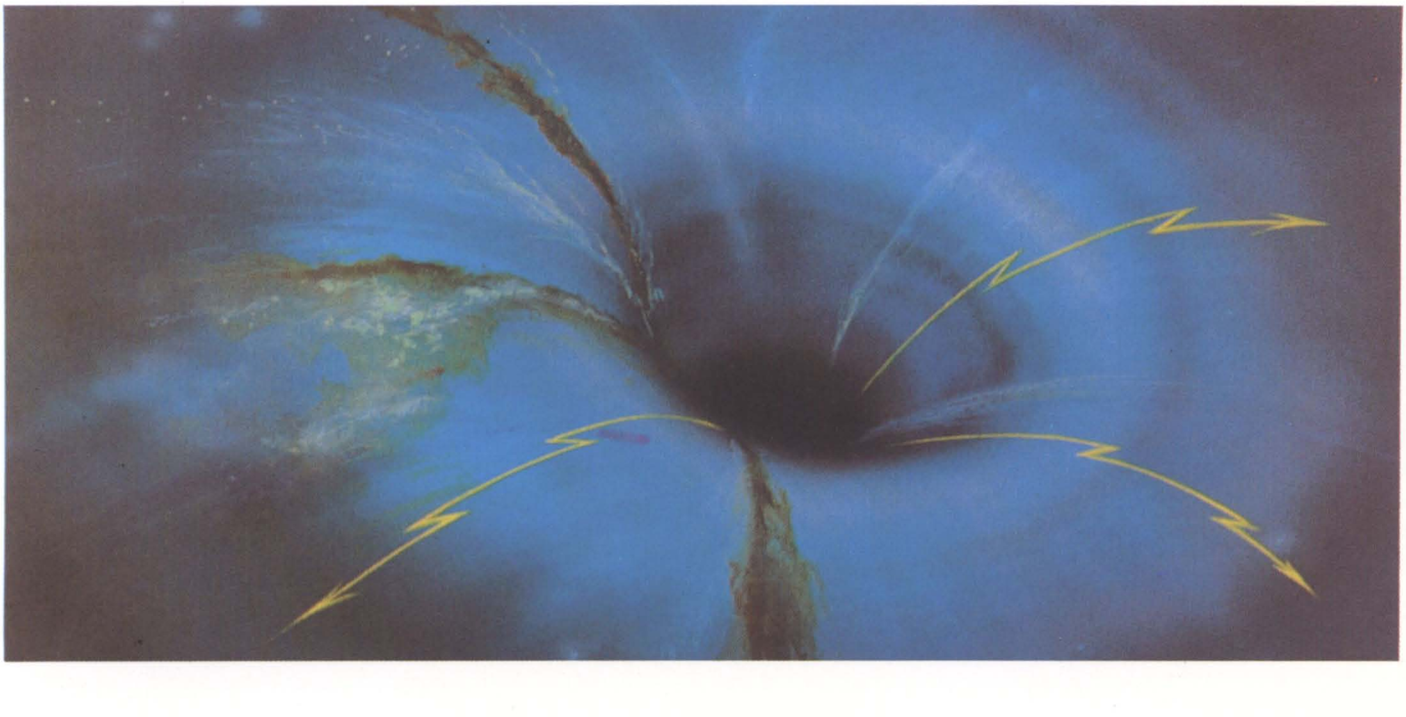
Within general relativity the 'gravity constant' G̦ is constant in time – or more precisely expressed, the coupling constant Gm^2/e^2 is constant in time. In other theories this is not so and gravitational clocks do not keep the same time as atomic clocks. Whether or not this is the case is an empirical question and can be answered by looking for a secular variation in the orbit of a planet as measured by atomic clocks. Such a variation cannot be disproved, but we can place upper limits on such variation by accurate monitoring of the planets over a long period of time.

9.5.6 Optical Interferometry in Space

An exciting future experiment is to measure the second-order

This artist's impression of a black hole (which is in reality not detectable in visible light) suggests how matter and even photons of energy are sucked in by the enormous gravitation of a black hole. Gravitational waves and gamma-ray observations are expected to tell us more about the processes thought to occur in the vicinity of a black hole and thus help to locate such objects.

Courtesy TRW.



light deflection by optical interferometry. Several concepts of optical interferometers with baselines ranging from 10 metres to several kilometres have been proposed (see Chapter 13). These are exciting possibilities as much for astronomy as for relativity, but they are perhaps projects for the 21st century.

9.5.6 Instrumentation

Accurate range and range-rate data are central to all space missions designed to probe our understanding of gravity. The effects of the interplanetary plasma can be calculated, provided two frequencies are used for both up- and down-links. The present Deep Space Network (DSN) has S (2 GHz) and X (8 GHz) band down-links, but only S-band up-link. However, this should be extended to include an X-band up-link for the Galileo mission. Further extension to higher frequencies (K-band or laser?) would be valuable as the S-band and X-band signals do not follow exactly the same path through the plasma.

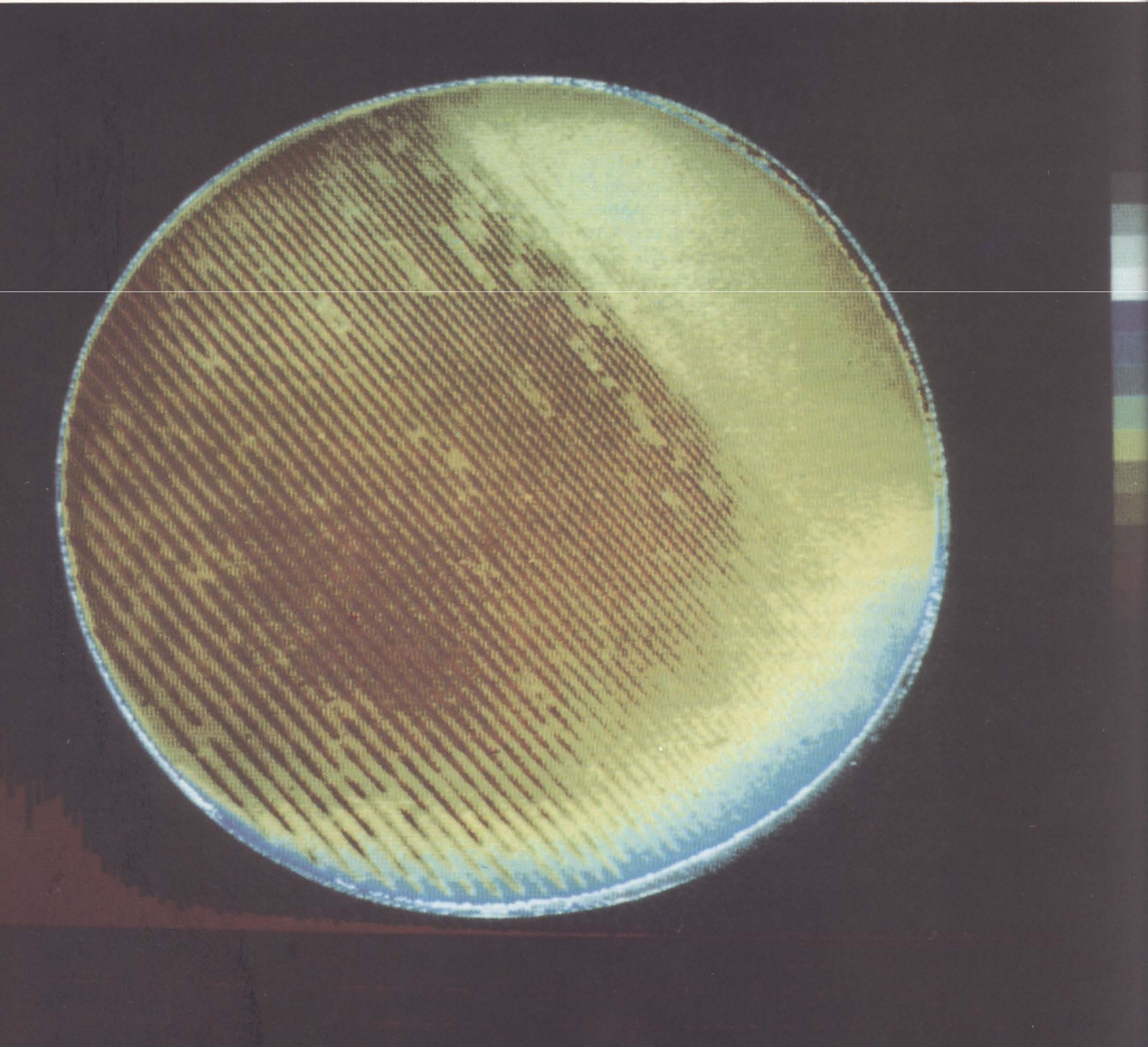
The limitation on tracking data comes from the effect of the troposphere. The best solution is to have an orbiting receiving antenna similar to that planned for VLBI experiments. However, improvement is possible by having an on-board clock and multiple link communication using time correlation analysis to estimate tropospheric effects.

The clock stability required for a second-order gravitational red shift experiment is 1 part in 10^{15} for averaging times of hundred of seconds to a few days. This is only an order of magnitude better than that achieved by the hydrogen maser on the Harvard-Smithsonian rocket experiment and similar to results achieved on the ground.

The effect of non-gravitational forces can be overcome either by a lander/orbiter experiment, or by a drag-compensation system. A drag-free system at the level of 10^{-8} cm/s^2 was flown in TRIAD over a decade ago, and even higher accuracies were envisaged in the ESA study on SOREL. For a mission going close to the Sun to measure the second-order gravitational red shift (and the solar quadropole moment and the effect of the solar angular momentum), the accuracy required is no higher than this, although the inhospitable environment poses some difficulties.

The analysis and interpretation of these very accurate experiments is extremely intricate and requires considerable expertise. Within the ESA countries, there are individuals and/or groups who have expertise in this area, partially as a result of the analysis of other proposed missions in conjunction with ESOC, and there should be no difficulty in putting together a group of relativists and celestial mechanicians to undertake the data analysis.

There is also the need to sustain a healthy programme of theoretical research in this field within Europe. Such theoretical studies should probe the foundations of theories (e.g. the metric hypothesis), identify new experiments for testing theories and for detecting gravitational waves, evaluate the feasibility and accuracy of such experiments, and determine their theoretical significance.



IUE image showing the high dispersion short wavelength (115–200 NM) spectrum of a hot star.

10. Technical Comments – Ultraviolet and Optical Instrumentation

J.M. Deharveng

In spite of the glamour of the Hubble Space Telescope (HST) and its optimisation for a wide range of astronomical observations, several outstanding problems have been identified which call for capabilities not provided by this observatory. These trends and the responses to the call for mission concepts make it possible to define a few broad categories of missions, and these will be discussed below.

10.1 Far and Extreme Ultraviolet Spectroscopy

The HST, optimised for use longward of 1150 Å, is inefficient for observing at shorter wavelengths, a unique domain where important spectral lines would permit the study of molecular hydrogen, deuterium and astrophysical plasmas in many objects over a wide range of temperatures. A high-resolution spectrograph in the 900–1200 Å region and, if possible, at shorter wavelengths in the extreme ultraviolet (EUV), has therefore been recognised as a crucial complement to the HST. The essential features of such a facility and the technical developments implied are summarised in Table 1.

Table 1. FUV and EUV Spectrograph Capabilities

Wavelength Range	Required	900–1200 Å
	Design goal	100–2000 Å
Spectral Resolution	High resolution	3×10^4 (900–1200 Å)
		10^4 ($\lambda>1200$ Å)
	Moderate resolution	500 (100–900 Å)
		2000 ($\lambda>900$ Å)
	Provides:	• Spectroscopic studies of important atomic and molecular transitions • Access to temperature regime from 10^4 to 10^7 K
Effective Area	Minimum 100 cm^2 Provides high-resolution spectroscopy of objects as faint as a 17th-magnitude quasar	
Angular Resolution	1 arc sec A long-slit capability ($\sim$40 arc sec) is required in the EUV for extended objects	
Development Areas	– Grazing-incidence telescope with 1 arc sec image quality – Coatings with acceptable reflectance are key factors in the trade-off studies and selection of spectrographs. Development programmes should include improved coating materials for better EUV reflectivity – Detectors: the availability of a long detector (or mosaïc), about 18000 pixels in length, may favour some of the spectrograph design concepts	
Context	Facility-class mission under a joint ESA/NASA study (Columbus UV)	

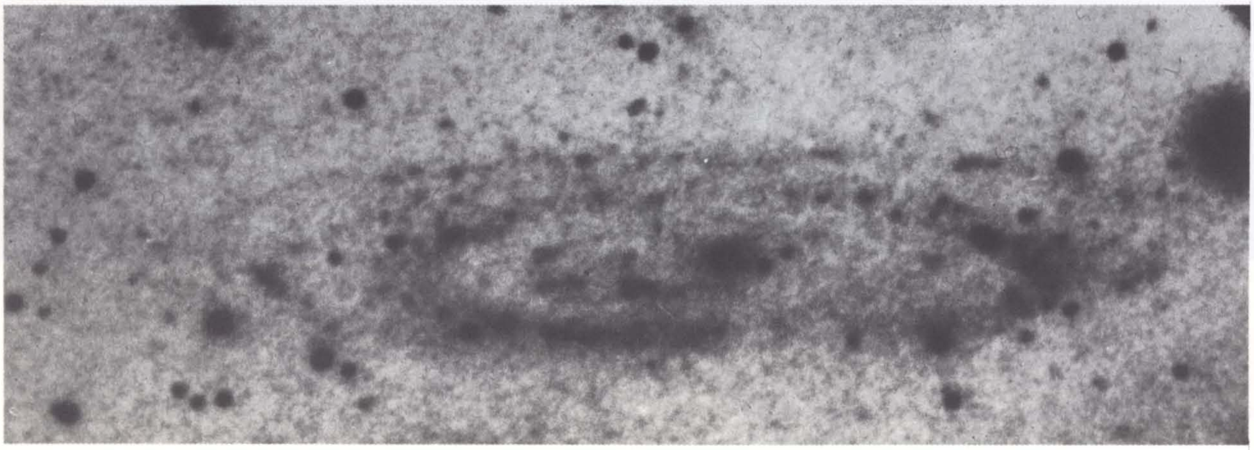
10.2 Wide-field UV Imaging

A second category of instrument would provide a deep UV imaging capability within a field of view much larger than the 2.7 arc min maximum offered by the HST. Typical characteristics are given in Table 2.

Table 2

Wavelength Range	1220–2000 Å, broadband
Spectral Resolution	Provides: selection of hot sources in the Universe
Field of View	Minimum 0°.5 Design goal 3°–5°
Angular Resolution	Maximum 3 arc sec Design goal 1 arc sec
Collecting area	1 m class telescope Provides a survey in the far-UV comparable to available ground-based surveys. Limiting magnitude V ∼26 for a B0 star in a 30 min exposure

This photograph of the galaxy M31 reveals the prominence at ultraviolet wavelengths (2000 Å) of young stars in the spiral arms over the older population in the central bulge.
(B. Milliard/Laboratoire d'Astronomie Spatiale).



10.2.1 Technical development

A version of this instrument, known as Space Schmidt, has been the object of an ESA assessment study (SCI(79)5). Crucial to this type of instrument would be the availability of a space-qualified detector with a large number of image elements. A small pixel size would also be an advantage. The amount of development needed is heavily dependent on the final trade-off between the angular resolution and the field of view.

10.2.2 Context

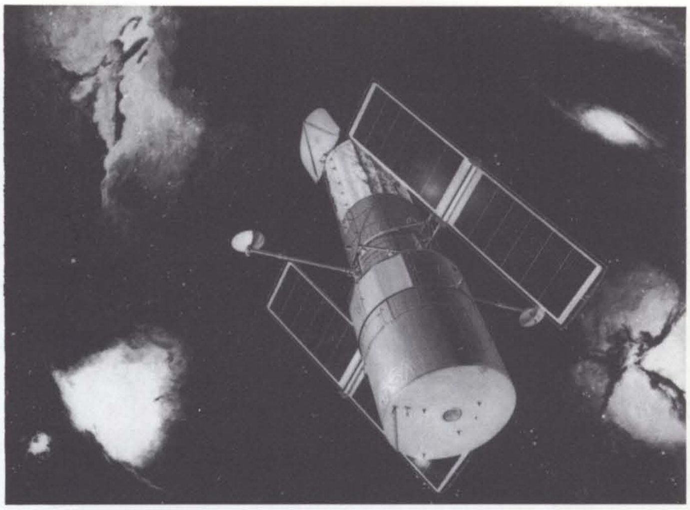
Because of the flight duration implied by a significant survey of the sky, the instrument could be launched as a free-flyer or mounted via a pointing system on a platform. A retrievable platform or a space station would permit the recovery of photographic or nuclear emulsions if materials with such high storage capacity were selected.

Such an imaging capability can also be considered desirable for the various intermediate-class observatories which have been proposed as a follow-up to IUE. With a performance superior to that of IUE and an improvement upon the HST performance in certain areas, such observatories would significantly increase, at moderate cost, the observing time available to the scientific community.

10.3 Far-Ultraviolet Spectroscopy of Extended Sources

As a result of its dedication to high angular resolution and faint limiting magnitude, the HST is unable to accommodate the large solid angles required for detecting very faint and extended sources (background radiation, haloes and extensions of galaxies, regions of shocks, ...). An instrument with the following features would permit such observations:

Wavelength Range	900–2000 Å Design goal 500–2000 Å Provides access to a spectral range where the local background (zodiacal light) is very weak
Spectral Resolution	~5 Å Provides spectral identification of the astrophysical processes involved
Field of View	Long slit (about 0°.1 × 4°)
Effective Area	About 5 cm² (at 1500 Å)
Technical Development	None



Hubble Space Telescope (HST).

10.3.1 Context

Owing to its low angular resolution, an experiment of this type is neither bulky nor demanding in terms of pointing and stabilisation. It could be accommodated as a 'piggy-back' to a major experiment or on a EURECA-type platform. Because of flight duration a Shuttle-borne instrument seems less appropriate.

10.4 Specific Experiments: Stellar Variability and Activity

Although some work on stellar variability and activity can be done from the ground on a limited sample of stars (e.g. by employing the Doppler-shift measurement technique on stars with low rotation velocities), only observations in space can provide both a long, continuous period of observations and the possibility of photometry limited by photon statistics. These characteristics are essential for the measurements of micro-magnitude brightness fluctuations over a large sample of stars. In addition, space observations would provide the possibility of monitoring stellar activity in UV spectral lines.

The essential features required for study of stellar variability and activity are not provided by existing and planned space missions. They clearly call for a dedicated experiment. The optical design (broadband photometer for brightness variability, high-resolution spectrometer working in a few spectral lines for activity measurements) seems straightforward. One development area is the achievement of very good photometric stability in the space environment. A trade-off study would have to determine the most advantageous orbit and mission considering the overall size and weight, the continuity and duration of observations, the variations in local environment, the pointing requirements etc.

10.5 Beyond the Hubble Space Telescope

Last but not the least, projects are proposed that would go beyond the most extreme capabilities of the HST. Ambitious optical interferometers aim at improving the angular resolution of the HST by several orders of magnitude. They are long-term projects and are discussed elsewhere in the context of space interferometry.


EXOSAT CMA (LEXAN 3000):
THE PUPPIS-A SUPERNOVA REMNANT

11. Technical Comments – X- and Gamma-ray Astronomy

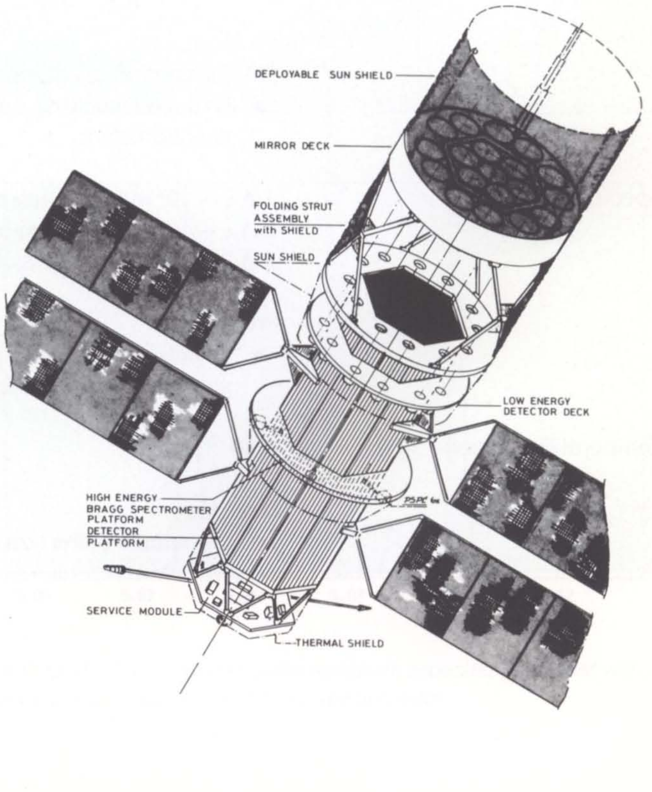
H.W. Schnopper

The set of goals set forth in the position papers concerning galactic and extragalactic astronomy and relativity and gravitation defines a framework of short- and long-range missions. State-of-the-art facility-class missions with ca. 10-year lifetimes are well within the capabilities of both ESA and the various research groups throughout Europe. Financial rather than technical limitations become the driving factors and within the proposed ESA budget profile it is only possible to think of facility-class missions being launched in the early to mid-1990s at best. Extremely attractive, smaller scale mission concepts are available, however, and they can be accomplished in a timely and cost-effective manner if they are designed to be flown on Shuttle-based reusable platforms such as an appropriately modified Eureca.

11.1 Facility-Class X-ray Missions

The centre of interest for a large European based X-ray astronomy mission is a high-throughput, modest spatial resolution, concentrator/spectrometer system which covers the broadest possible wavelength range. Such a mission, which ESA has assessed (XMM), is completely complementary to the NASA AXAF mission and with both satellites flying during the same time frame the fullest programme of X-ray astrophysical observations will be available. The scientific objectives suggested in the position papers lead to the design goals listed in Table 1 which, with some modification, have come out of the XMM Assessment Study. The most significant change has been the extension of the energy range to $\sim$20 keV. This upper limit is inherent in the XMM design, but was not given emphasis in the Assessment Study. It is clear now that $\sim$30 arcsec imaging, broad and narrow band spectroscopy, and good sensitivity at $\sim$20 keV, become important design goals.

The Instrument Technology Verification Phase of the XMM programme represents an innovation in ESA studies and it has not yet been approved by management. This phase would contain the normal Phase-A activity but, most importantly, would contain a technology verification phase lasting about 3.5 years, during which the critical designs are developed to the standard of a good Engineering Model with which the instrument performance could be verified.



The X-ray Multi-Mirror Mission (XMM).

Table 1. Design Goals

Facility Class X-Ray Mission

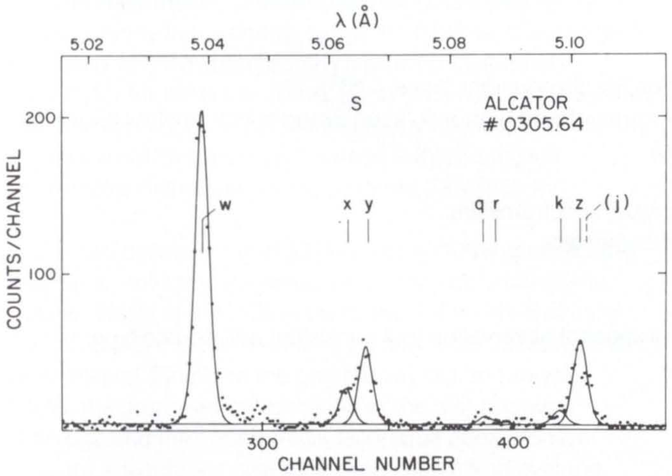
Energy (Wavelength) Range	0.1–20 keV (100 Å – 0.5 Å) Provides: • Diagnostics of astrophysical plasmas in the temperature regime above one million Kelvin, including emission lines up to hydrogen-like iron (Fe XXVI)
Effective Area	$\gtrsim 10^4$ cm^2 at $\sim$2 keV $\gtrsim 5\times10^3$ cm^2 at $\sim$7 keV (Fe XXVI) $\gtrsim 10^3$ cm^2 at $\sim$20 keV Provides: • Sensitivity 10^{-15} erg cm^{-2} s^{-1} in 10^4 s in 0.5–5 keV band • Very high photon collecting area required for detailed spectroscopy or for variability studies of faint sources.
Fields of View	0°.5 high energy >2 keV 1° low energy <2 keV Provides: • Required solid angle for study of extended X-ray sources/features like SNR, ISM, galaxy clusters, diffuse background.
Angular Resolution	10 arc sec HPW at 2 keV 30 arc sec HPW at 7 keV (Fe XXVI) Provides: • Elimination of source confusion for observation times $\lesssim 10^4$ s. • Required resolving power for wide-band medium resolution spectroscopy with grating spectrometers.
Spectral Resolution	$\lambda/\Delta\lambda \sim 10^3$ with high-resolution crystal spectrometers $\lambda/\Delta\lambda \sim 10^2$ with medium-resolution grating spectrometers $\lambda/\Delta\lambda \sim 10$ with low-resolution spectrometers. Provides: • Selection of the most powerful spectral observation tool consistent with source type, strength and variability.
Temporal Resolution	$\lesssim 10^{-3}$ s Provides: • Signatures of the size and nature of the X-ray source.

11.1.1 Technology Verification – X-Ray Astronomy

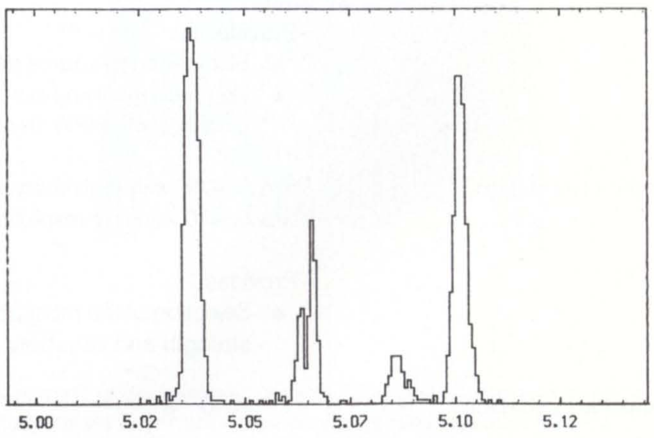
During the Technology Verification phase, the following specific activities are foreseen:

Technology Verification – X-Ray Astronomy

Mirror studies	
Carbon-Fibre Replica Reflectors	• Study of the replication technique using CFRP as the carrier. • Study of mirror design in view of the large scale of shells (ca. 300) that will be needed. • Study of mirror quality variations with changes in temperature and over an extended period of time.
Thin Foil Reflectors	• Study of materials suitable for the manufacture of the shells. • Study of a direct manufacturing process using CFRP. • Design and manufacturing studies and assessment of the mechanical and optical characteristics of a representative mirror assembly.
Instrument Studies	
Solid-State Detectors	• Study of the basic detector technologies to establish, in particular, the change of characteristics with time. • Study of mechanical refrigerators, such as those based on the Stirling Cycle.
Bragg Crystal Spectrometers (BCS)	• Study and test of representative crystals. • Study of mechanism concepts.
Position-Sensitive Gas Scientillators (PSGS)	• Study of readout methods. • Study of the window-thickness/gas-loss relationship. • Study of their window instrument performance.
Position-Sensitive Proportional Counters (PSPC)	• Study of readout methods.



The spectrum of He-like sulfur obtained by Källne et al. (Phys. Res. A, 1983).



A simulation of the He-like sulfur spectrum expected from XMM with an improved version of the same spectrometer.

11.2 Explorer-Class X-ray Missions

It is clear that the Facility-Class X-ray Mission will not fly until the mid-1990s. It is also clear that the XMM technology verification phase will produce instruments which could be assembled into a mission capable of providing answers to some of the significant questions raised in the scientific papers. Within this class of mission there exist (or recently have existed) several national missions: HTS (UK), SAX (I, NL), ROSAT (D), XTE (USA), ASTRO C (J) and the ESA X-80 mission. In addition, the responses to the Survey Questionnaire combine many of the features of these missions. Those expected to fly are:

ROSAT (D):	a telescope all-sky survey in XUV and soft X-rays up to ~1.5–2 keV.
XTE (USA):	large-area proportional counters for timing and broadband spectroscopy.
ASTRO C (J):	similar to XTE.

Table 2 Design Goals

Explorer-Class X-Ray Mission

Energy (Wavelength) Range	0.1–10 keV Provides: • Diagnostics of astrophysical plasmas in the temperature regime above one million Kelvin, including emission lines up to hydrogen-like iron (Fe XXVI)
Effective Area	$\gtrsim$800 cm^2 at ~2 keV $\gtrsim$500 cm^2 at ~7 keV Provides: • Sensitivity ~5×10^{-14} erg cm^{-2}s^{-1} in 10^3s in 0.5–5 keV band
Fields of View	0.5 all energies Provides: • Required solid angle for study of extended X-ray sources/features like SNR, ISM, galaxy clusters, diffuse background.
Angular Resolution	<2 arc min Provides: • Elimination of source confusion for observations times $<10^3$ s. • Required resolving power for narrow band high-resolution Bragg spectrometers (Gratings possible with HPW 10 arc sec).
Spectral Resolution	$\lambda/\Delta\lambda$ ~10^3 with high-resolution crystal spectrometers. $\lambda/\Delta\lambda$ ~10 with low-resolution spectrometers. Provides: • Selection of the most powerful spectral observation tool consistent with source type, strength and variability.
Temporal Resolution	$\lesssim 10^{-3}$ s Provides: • Signatures of the size and nature of the X-ray source.

In the event that an ESA mission complementary to the national programmes is envisioned, a set of design goals that could be achievable in a mission for launch by 1990 is given in Table 2. These goals are accomplished by using thin-foil concentrators with PSPC, PSGS and BCS elements at the focus of the concentrators. A modified EURECA would be an ideal platform for this mission.

11.3 Explorer-Class missions in the Hard X- and Gamma-Ray Regime

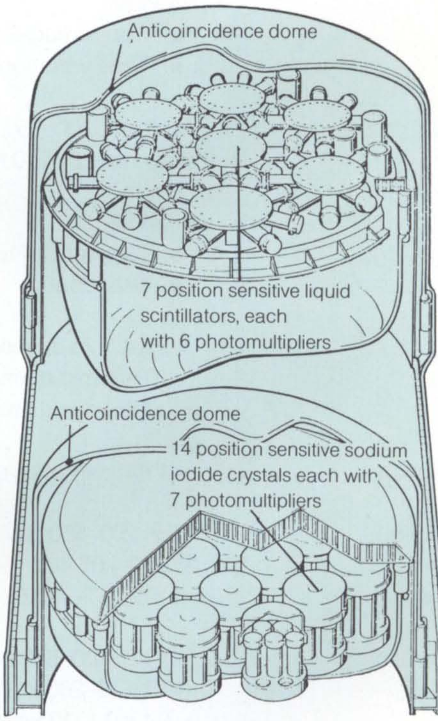
The mission concepts presented for the hard X-ray regime (20 keV–10 MeV) can be broadly divided into two groups:

- '*Survey-type Instruments*' with large FOV, random mask or RMC coding of the image, moderate energy resolution ($\Delta E/E \sim 10\%$), large background rates and resulting very low signal-to-noise ratio ($\lesssim 10^{-3}$) for sources at the limiting sensitivity.
- '*Spectroscopy-type instruments*' with small FOV, Bragg (reflection or transmission) concentrators, high energy resolution ($\Delta E/E \sim 0.5\%$) and a signal-to-noise ratio of 0.1–1 at the limiting sensitivity.

Both mission concepts have an important part to play in the future of X-ray astronomy, but in setting priorities for an ESA programme one should note that there are already two collaborative efforts on the first type of mission between some ESA countries and the Soviet Union (Intercosmos) whereas the second type is still in its infancy, but carries a great potential if properly developed. The first type is less demanding in terms of pointing requirements than the second, and therefore it may be the preferred choice for a national or bi-national programme.

It appears likely that on a mission primarily intended for hard X-ray astronomy in the energy range 10–550 keV, it would be scientifically very advantageous if a grazing-incidence concentrator for the 0.1 to 10 keV band were also carried. From the technical point of view, the low-energy telescope would not impose new constraints on the carrier. Table 3 outlines scientific aims of this type of 'broad-band X-ray mission'.

For energies between 1 and 30 MeV, concentrating telescopes presently do not appear feasible and it may be advisable to await the results of the SIGMA experiment (French–Russian) and GRO (NASA) before deciding on new experiments in this energy interval. Finally, in the gamma-ray region (above 30 MeV), the proposed combination of the drift-chamber technology and the coded-mask technique does promise significant advantages over past experiments and over the GRO experiment also. However, a mission dedicated to this field would serve a rather small community – the number of observations made during a two-year mission would be about an order of magnitude less than for the missions discussed above.



Schematic of the Imaging Compton Telescope (Comptel) designed to study the sky in the light of low-energy gamma rays from NASA's Gamma-Ray Observatory (GRO). The Comptel Collaboration comprises MPE Garching, ROL Leiden, the University of New Hampshire, and the Astrophysics Division, Space Science Dept. ESA.

Table 3 – Design Goals

Explorer-Class Mission, Broadband, with Emphasis on Hard X-rays 10–550 keV

Energy Ranges:	200–550 keV Provides: • Diagnostics of astrophysical pair plasmas in AGNs, pulsar magnetospheres and annihilation-line astronomy in the Galactic Centre, pulsars and other sources. • Time variability of spectrum and intensities. 10–200 keV Provides: • Diagnostics of astrophysical plasmas around compact galactic and extragalactic objects. • Cyclotron line astronomy in pulsars. • Time variability. 0.1–10 keV Provides: • Supporting diagnostics for above. • Time variations.
Effective Area:	$\sim$50 cm^2 200–550 keV, 200 cm^2 10–200 keV. $\gtrsim$200 cm^2 0.1–10 keV. Provides: • Line sensitivity: $\sim 10^{-5}$ ph/cm^2 s at 10^5 s • Broadband $\sim 10^{-6}$ ph/cm^2 s keV at 10^5 s
Fields of View:	$\sim$2 arc min diameter 200–550 keV $\sim$10 arc min diameter 10–200 keV $\sim$30 arc min diameter 0.1–10 keV
Angular Resolution	$\sim$1 arc min at all energies
Spectral Resolution:	0.5% 200–550 keV 3% 10–200 keV $\gtrsim$10% 0.1–10 keV
Temporal Resolution:	$\sim$100 s 200–550 keV $\sim$10 s 10–200 keV $\sim$0.1 s 0.1–10 keV

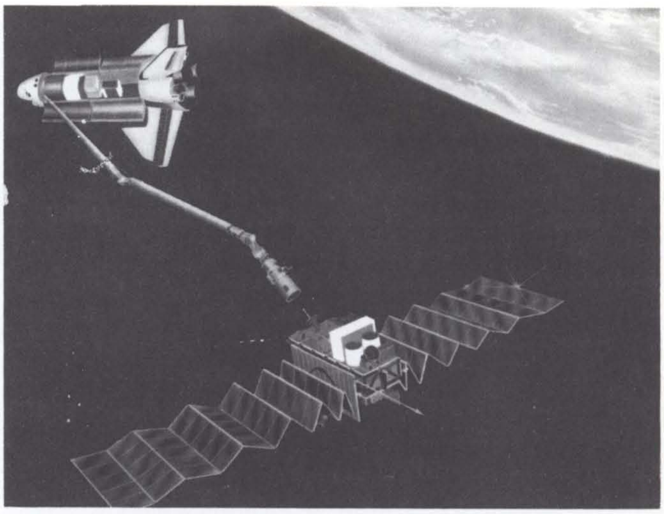
11.4 EURECA – Appropriately Modified

The EUropean REtrievable CArrier is a Shuttle-launched, reusable free-flying platform, developed for initial use as a microgravity facility. A modified version with improved performance characteristics is being studied for an astronomy payload. It provides the following improvements:

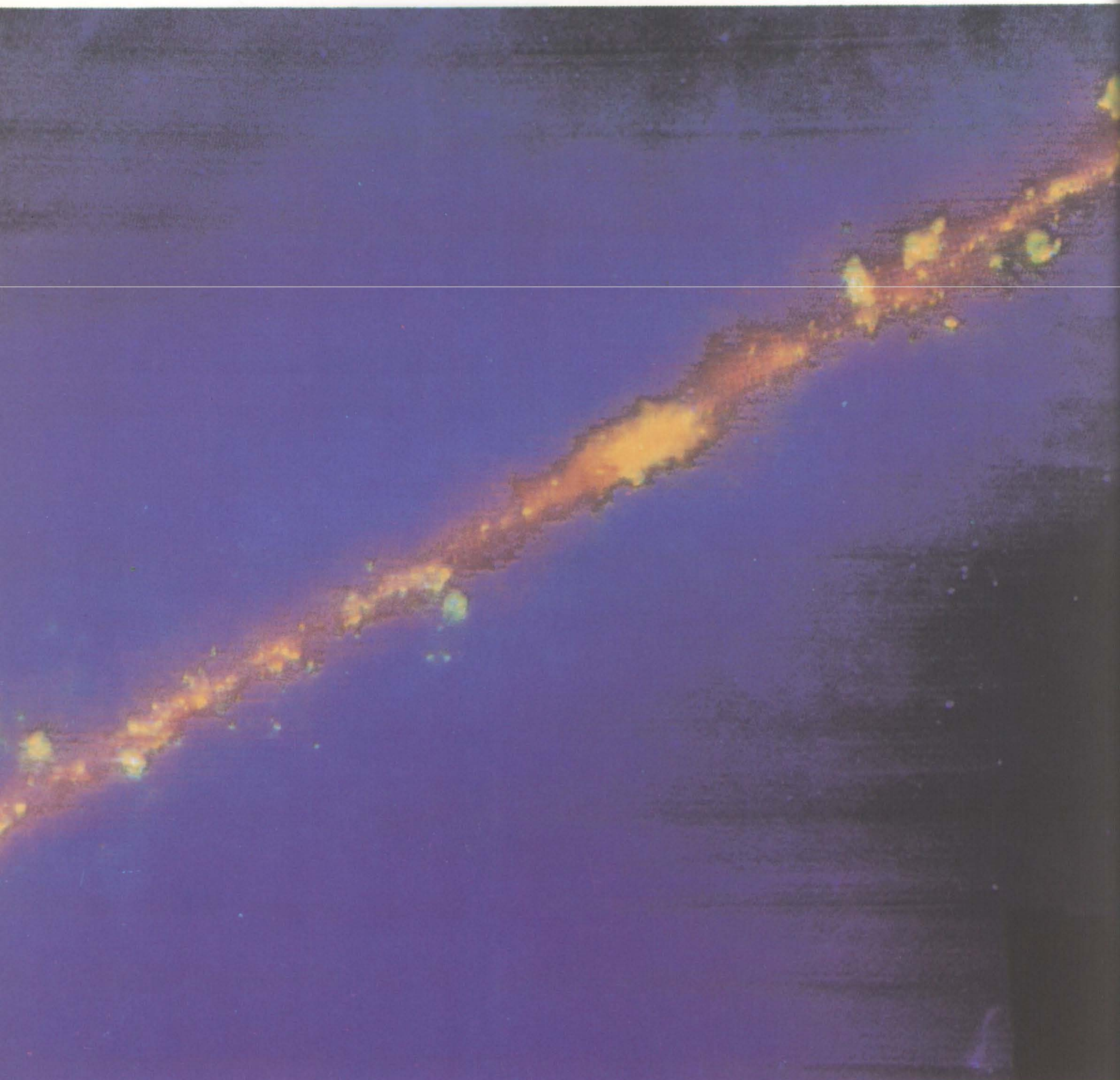
Pointing accuracy	0.1° (6 arc min)
Stability	0.3 arc sec/s
Reconstitution accuracy	0.02 deg (1 arc min)
Data rate	50 kbit/s
Orbit	28.5° inclination

These are fully compatible with the objectives of an explorer-class X- or gamma-ray mission.

The possibility of a co-operative mission, with NASA providing launch, operations and retrieval, is financially attractive and, at the moment, represents a cost effective route towards an explorer-class X-ray mission.



An artist's impression of Eureca being retrieved by the Shuttle Orbiter.



This is an IRAS image of the centre of our galaxy, the Milky Way. The yellow and green knots and blobs scattered along the band are giant clouds of interstellar gas and dust heated by nearby stars. Some are warmed by newly formed stars in the surrounding cloud, and some are heated by nearby massive, hot, blue stars that are tens of thousands of times brighter than our Sun. Red areas represent regions dominated by cold gas and dust. The large yellow bulge near the middle is the centre of the galaxy

Courtesy of NASA-JPL

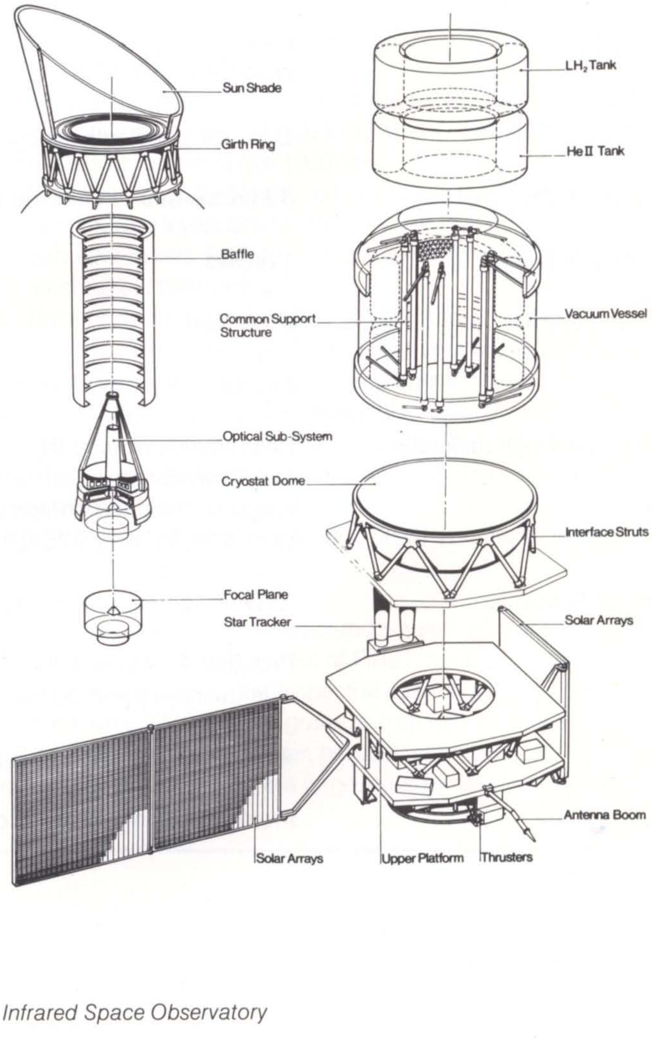
12. Technical Comments – Infrared, Submillimetre and Radio Astronomy

G. Winnewisser

The submillimetre wavelength range (λ=1 mm – 0.1 mm) is the last major window of the electromagnetic spectrum to be opened to scientific studies. The astrophysical objectives in this wavelength range encompass spectroscopic studies of atoms and molecules of galactic and extragalactic objects, covering specific details of star formation in individual molecular clouds, the determination of the present rate of expansion of the Universe (Sunyaev-Zeldovich effect), and studies of the solar system itself (planets).

12.1 Submillimetre Telescope

The scientific objectives accomplished by IRAS clearly point the way for ISO and missions planned for the future, such as FIRST. In particular, the low and medium angular resolution capabilities of IRAS and ISO will be surpassed by a large telescope such as FIRST, which will be operating in the submillimetre wavelength range. The proposed smaller SMIT (Submillimetre Telescope) is a scaled-down version of FIRST in telescope diameter (2 m), wavelength coverage (200 μm – 2.5 mm) and instrumentation (grating Fourier spectrometer). A state-of-the-art submillimetre wave telescope will complement IRAS and ISO.



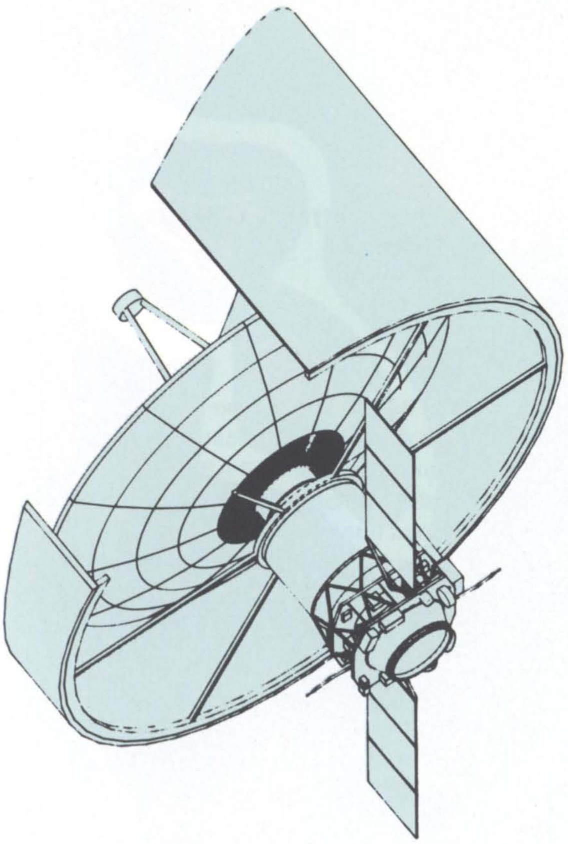
Infrared Space Observatory

Telescopes of the FIRST class are presently technically feasible as regards both the antenna design concept and the focal-plane instrumentation. Table 1 summarises the essential features of FIRST, which is now entering the technology-verification phase.

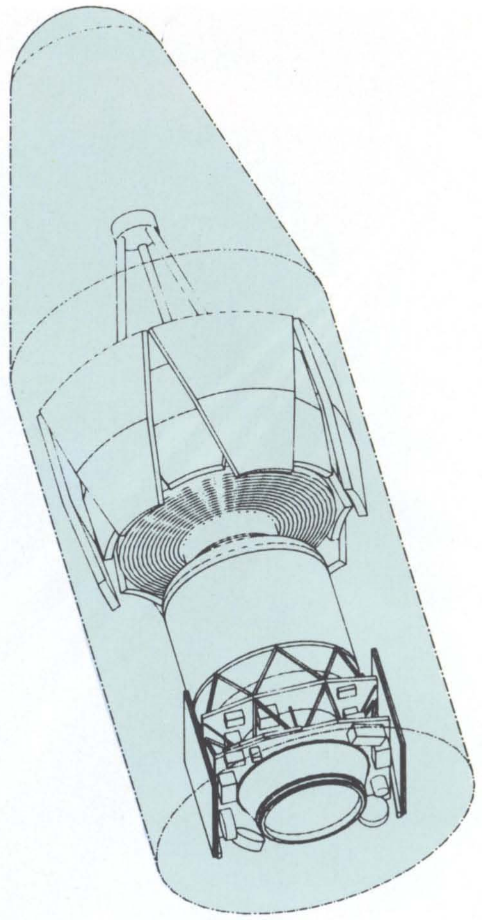
Table 1 – Design Goal

Submillimetre Telescope

Wavelength – Frequency Interval	ca. 1 mm – 0.1 mm 500 GHz – 3000 GHz
	Provides: Access to galactic/extragalactic objects in temperature region 10 K – 3000 K. Diagnostic tool for molecular clouds – atoms, molecules, ions Continuum radiation from dust
Telescope Size	8 m – deployable
	Provides: Hitherto unparalleled angular resolution High Sensitivity: 10 mJy at 0.1 m
	Difficulty: panel adjustment, long-term panel adjustment and accuracy
Angular Resolution	3.2 arcsec at 0.1 mm diffraction limited
Pointing Accuracy	1 arcsec
Pointing Stability	0.5 arcsec
	Provides: Resolution of small and clumped interstellar material.
Focal-Plane Instrumentation	Heterodyne package (500 – 2000 GHz) Short-wavelength spectrometer (0.1 – 0.2 mm) Imaging multiband photometer (λ = 0.05, 0.1, 0.15, 0.25, 0.9, 1.6 mm)
Spectral Resolution	$\lambda/\Delta\lambda = 10^6$ (superheterodyne)
	Provides: Access to extremely narrow lines (i.e. maser, etc.) in frequency region: 500 GHz – 20 000 GHz
	$\lambda/\Delta\lambda = 10^4$ (short wavelength spectrometer)
	Provides: Survey character of short-wavelength portion (λ = 0.1 mm – 0.5 mm)



First study - deployed configuration



First study - stowed configuration

12.2 Technology Verification Plan – Infrared and Submillimetre Astronomy

12.2.1 Antenna studies

a) Panel technology: The development of antenna panels with the required surface finish and ability to perform in space, especially with regard to the thermal environment.
b) Assembly and alignment on Earth: The antenna must be capable of supporting itself and being set up to the required accuracy under the 1 g environment.
c) Deployment schemes: Because of the restrictions due to launcher shroud dimensions, the antenna cannot be made as a single fixed dish. Methods of folding and deploying it have therefore to be studied.
d) Alignment and control: During the operational period in-orbit methods have to be used to maintain the antenna's performance despite the residual effects of launch loads and the changing thermal environment.

12.2.2 Instrument studies

a) Type of mixer for heterodyne package: Study of performance of SIS-, SIN- and Schottky-mixers in the submillimetre-range.
b) Local oscillators for heterodyne package: Development of lightweight carcinotrons up to 1000 GHz. Development of harmonic mixers above 1000 GHz.
c) Cryogenics: Study of required cryogenic power at different temperature levels (2 K for SIS/SIN-mixers, 20 – 80 K for Schottky-mixers, 0.3 K for imaging photometer). Study of mechanical refrigerators.
d) Back ends: Reduction of size, weight and power consumption of acousto-optic spectrometers (AOS). Study of performance of chirp-transform spectrometers.
e) Short Wavelength Spectrometer: Size reduction of instrument, optimising the use of many (50) detectors, resolution improvement, extension to shorter and longer wavelength.
f) Multiband Imaging Photometer: Study and improvement of detector arrays.

It is possible to think about dedicated smaller missions pertaining to one special aspect of FIRST, such as spectroscopic studies at high spectral resolution, or medium resolution only. SMIT is a programme that falls into this explorer-type mission. However, present technological capabilities are available for a large state-of-the-art mission.

13. Technical Comments – Interferometry Missions

R.T. Schilizzi

The position papers on Astronomy and Relativity and Gravitation target space interferometry as one of the areas of importance in the ESA Science Programme in the coming decades. The interferometry technique is well established in ground-based radio astronomy, and has provided ever-increasing angular resolution as techniques progressed from cable-linked two-element interferometers, through multi-element radio-linked interferometers, to Very-Long-Baseline Interferometry (VLBI), where the size of the Earth provides the only limit to the separation of elements.

13.1. Very-Long-Baseline Interferometry (VLBI)

That VLBI is successful at all, demonstrates that there is no fundamental technical barrier to extending baselines into space. There are strong scientific reasons for doing so and the Quasat mission responds to these requirements. It is designed to provide images of the total intensity and polarised emission of compact radio sources in continuum and line, with a combination of angular resolution and quality that is unattainable on Earth. The astrophysical goals encompass the study of active nuclei at scales appropriate to the outer reaches of accretion disks and the optical broad line regions, the study of galactic continuum sources in stars and in the Galactic Centre, and spectroscopic studies of galactic and extragalactic molecular masers to determine their role in the life cycle of stars, and their use as direct distance indicators. Table 1 lists the design goals of an orbiting VLBI element, which are derived from these astrophysical objectives.

Achieving even higher resolution in the radio means going to shorter wavelengths and longer baselines. Tables 2a and 2b list the design goals for two millimetre-wavelength VLBI missions; one, a ten times higher frequency follow up to Quasat, which would operate in conjunction with ground-based millimetre wave telescopes, the other a three-element array operating entirely in space with element separations of up to 10^5 km. Angular resolutions of 1 μarcsec could, in principle, be achieved.

Optical interferometry on the ground has been less successful than in the radio due to the effects of atmospheric turbulence in the light paths. Going into space is the only way open to high angular resolution in the optical. Again, two different concepts have been proposed, with design goals listed in Tables 3a and 3b. The first is a two-dimensional multi-element optical array with element separations of up to 500 m and operating via the principles of aperture synthesis, the other a free-floating two-element Michelson interferometer with baselines up to 10 km. At the shortest wavelengths the resolution of the first system is $\sim$0.1 milli-arcsec, and of the second $\sim$10 μarcsec.

The time scales for development of the mm-VLBI and optical interferometry missions are clearly considerably longer than for QUASAT. Support within the Instrument Technology Verification Programme is required for the long-term development of interferometry in space, in order to ensure technological convergence of these 'blue-sky' concepts.

Artist impression of orbiting radio telescope (Quasat) in Very Long Baseline Interferometric (VLBI) network (courtesy JPL).

Table 1. Design Goals

Centimetre-Wavelength Orbiting VLBI Antenna

Wavelengths	1.35 cm	6 cm	18 cm
Frequency Ranges	22.0 – 22.5 GHz	4.72 – 5.02 GHz	1.60 – 1.72 GHz

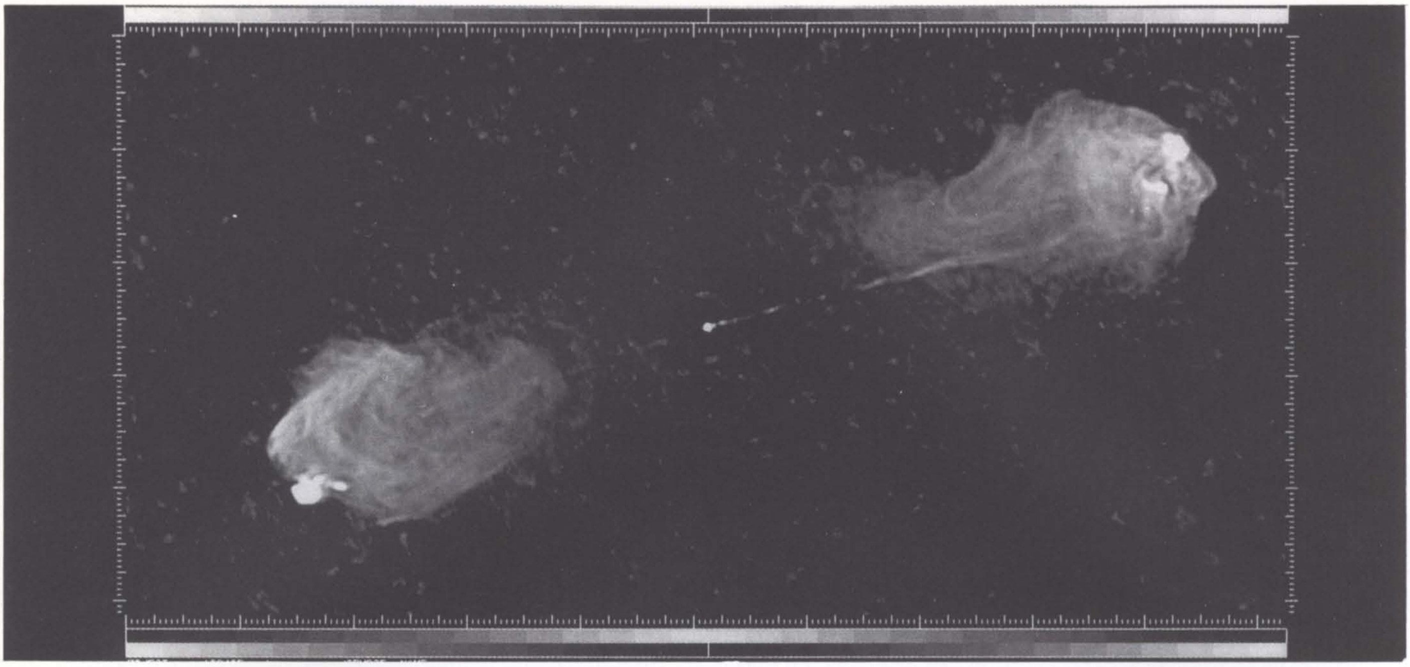
	Provides: • Wavelengths in common with the ground-based radio telescopes so that interferometer combinations can be made with those telescopes for very high resolution, high quality continuum images of compact radio sources. • The capability for measuring opacity effects in compact objects by continuum observations in the three wavelength bands. • Wavelengths at which spectral line observations of maser sources (due to H_2O (22 GHz) and OH (1.612, 1.665, 1.667, 1.720 GHz) can be made in protostars and in evolved stars.
Polarisation	Both hands of circular polarisation to be received simultaneously. Provides: • Diagnostic information on the magnetic field strength and direction, and, from the variation of the percentage polarisation and orientation of the electric vector as a function of wavelength, the density of thermal electrons in the line of sight.
Angular Resolution	75 μarcsec at 1.35 cm 0.3 marcsec at 6 cm 0.9 marcsec at 18 cm Provides: • Linear resolutions of 1 AU at the Galactic Centre and $\leqslant 10^{17}$ cm at distances up to $\sim$100 Mparsec. • Similar angular resolution at 6 cm to that achieved at 1.35 cm with ground arrays alone, and at 18 cm, a similar resolution to ground-based 6 cm observations. Allows measurement of opacity effects in extended structure.
Spectral Resolution	256 channels per interferometer Provides: • Spectral resolution of 0.2 km/s over a velocity range of 50 km/s. Wider velocity coverage can be obtained by retuning the receiver.
Aperture Plane Coverage	Dense coverage of the aperture (U-V) plane. Provides: • Circular interferometer beam (or point spread function) with low sidelobes. • Very high quality images at all declinations. • Capability for moderate quality images from short (snapshot mode) observations of 6 h duration.
Fields of View	• 20 marcsec at 1.35 cm. • 100 marcsec at 6 cm. • 0.25 arcsec at 18 cm.

Mapping Time	• 6 h for variable galactic sources. • 12–48 h for other sources depending on intensity and structural complexity.
Sensitivity	Antenna diameter ⩾15 m, with surface accuracy ⩽0.8 mm; Receiver system temperature ⩽150 K at 1.35 cm, ⩽75 K at 6 cm, ⩽40 K at 18 cm. Signal bandwidth 32 MHz. Provides: • RMS noise in a 1.35 cm continuum map of ⩽1 mJy, ⩽0.5 mJy at 6 cm and ⩽0.3 mJy at 18 cm, after a 48 h observation, provided there is a strong enough feature present in the map to allow self-calibration. Requirements for the latter are: ~150 mJy at 1.35 cm, and ~50 mJy at 6 and 18 cm. • RMS noise per spectral channel of ~70 mJy at 1.35 cm and ~40 jMy at 18 cm, after a 48 h observation, provided there is a spectral feature present of sufficient strength to allow self-calibration. Requirements for the latter are 40 Jy at 1.35 and 10 Jy at 18 cm.

Table 2. Design Goals

a. Millimetre-Wavelength Orbiting VLBI Antenna

Wavelength Range	1–10 mm (30–300 GHz) Provides: • Wavelengths in common with present and future ground-based millimetre-wave radio telescopes so that interferometer combinations can be made with those telescopes for extremely high resolution, good quality continuum images of compact radio objects. • The ability to measure opacity effects in compact objects by continuum observations at different wavelengths.
Angular Resolution	5 μarcsec at 1 mm 50 μarcsec at 10 mm Provides: • Linear resolutions of ~10^{12} cm at the Galactic Centre and ⩽2×10^{16} cm (⩽10 light days) at distances up to 100 Mparsec.
Aperture Plane Coverage	Dense coverage of the aperture (U-V) plane. Provides: • Circular interferometer beam (or point spread function) with low sidelobes. • Good-quality images at all declinations. • Capability for moderate quality images from short observations of 6 h.
Mapping Time	• 6 h for variable galactic sources • 12–48 h for other sources, depending on intensity and structural complexity.
Sensitivity	Antenna diameter 15 m, with surface accuracy of 60 μm; cooled receivers with system temperatures 100 K at 1 mm and 50 K at 10 mm; Signal bandwidth 100–1000 MHz. Provides: • RMS noise in a continuum map of ⩽5 mJy at 1 mm and ⩽1 mJy at 10 mm after a 48 h observation, provided there is a strong enough feature present in the map to allow self-calibration. Requirements for the latter are: ⩽1 Jy at 1 mm and ⩽150 mJy at 10 mm.

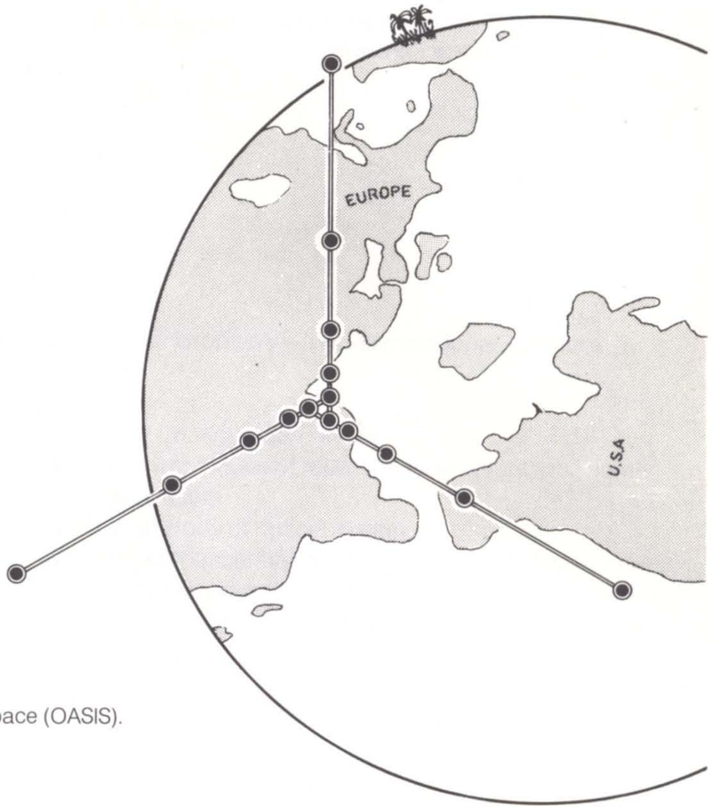


'Radiograph' of Cygnus A at 6 cm made with the Very Large Array (VLA) New Mexico (courtesy - R.A. Perby, J.W. Dreher and JPL).

Table 2. Design Goals

b. Three-element VLBI Array of Orbiting Millimetre-Wavelength Antennas

Wavelength Range	1 – 10 mm (30 – 300 GHz). Provides: • Wavelengths at which ultra-high-resolution, moderate quality, continuum images of compact radio sources can be made. • The ability to measure opacity effects in compact objects by continuum observations at different wavelengths.
Angular Resolution	1 μarcsec at 1 mm. 10 μarcsec at 10 mm. Provides: • Linear resolutions of $\geqslant 2 \times 10^{11}$ cm ($\geqslant$5 light seconds) at the Galactic Centre and $\geqslant 2 \times 10^{15}$ cm ($\geqslant$1 light day) at distances of 100 Mparsec.
Aperture Plane Coverage	• As good as possible with only three elements and orbits of 100 000 km.
Mapping Time	• 20 to 40 days per object, to get as good aperture plane coverage as possible.
Sensitivity	Antenna diameter 15 m, with RMS surface accuracy of 60 μ; cooled receivers with system temperatures of 100 K at 1 mm and 50 K at 10 mm; signal bandwidth 100 – 1000 MHz. Provides: • RMS noise in a continuum map of order 10 mJy at 1 mm, and 5 mJy at 10 mm after a 40 day integration.



Optical Aperture Synthesis in Space (OASIS).
(Courtesy J.E. Noordam et al.).

Table 3. Design Goals

Optical Interferometry in Space

(a) Two-Dimensional Aperture Synthesis with a Redundant Spacing Array	
Wavelengths	1200 – 10 000 Å
Angular Resolution	⩽0.1 marcsec at 1200 Å. ⩽1 marcsec at 10 000 Å.
Aperture Plane Coverage	Instantaneous two-dimensional coverage. Provides: • Linear resolution of $\geqslant 1.5 \times 10^{13}$ cm (10 light mins.) at the Galactic Centre $\geqslant 2 \times 10^{16}$ cm at the Virgo cluster (15 Mpc), and $\geqslant 1.5 \times 10^{17}$ cm at 100 Mparsec. This resolution is appropriate for study of, for example, broad-line regions in galactic nuclei. • Good-quality images with a circular point spread function.
Sensitivity	1 m diameter elements. 5000 Å bandwidth; 10% optical efficiency; 10% detector quantum efficiency, 1 s sample time for calibration. Provides: • Ability to use 12^m stars as reference objects for calibration, once per second, of the phase behaviour of the interferometer using the redundant spacings in the interferometer. • Capability of imaging in continuum and spectral lines. • SNR of 5 per U-V point per Å per hour on an m = 16.5 object.
Fields of View	1 square degree for the calibration fields. 1″ × 1″ for the central field to be imaged.

An Inflatable Antenna under consideration for Quasat.
(Courtesy Contraves).

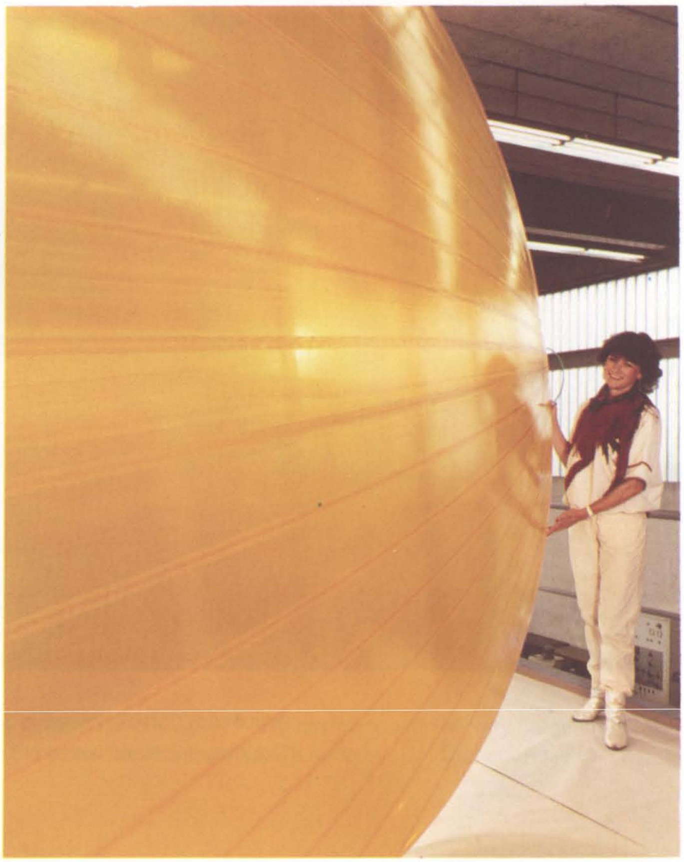


Table 3. Design Goals

Optical Interferometry in Space

(b) Two-Element Michelson Interferometers

Wavelengths	4000 – 20 000 Å.
Angular Resolution	⩾5 μarcsec at 4000 Å. ⩾20 μarcsec at 20 000 Å. Provides: • Diameters of the objects with linear resolution of ⩾5×10^{11} cm (⩾20 light seconds) at the Galactic Centre, ⩾10^{15} cm (0.5 light day) at the Virgo cluster (15 Mparsec), and >1.5×10^{15} cm at 100 Mparsec. This resolution is appropriate for study of emission on accretion disk scales in galactic nuclei. • Crude images for objects of particular importance.
Sensitivity	1 m diameter elements with 20% optical efficiency, 5000 Å bandwidth, 20% detector efficiency, 10 000 s integration. Provides SNR of 5 per U-V point / Å / hour on an m=16.5 object.
Field of View	Several seconds of arc for baselines up to a few hundred metres, and decreasing with increasing baseline.

13.2. Instrument Technology Verification Programme

Quasat

Antenna Study

- The two competing technologies of an Inflatable Space Rigidisable Structure (ESA), and a Deployable Wrap-Rib Mesh Reflector (NASA) need to be evaluated in detail and a choice made between the two, before a joint ESA/NASA Phase-A study can begin. The date foreseen for this decision is June 1985.

Millimetre Wavelength Space VLBI

Antenna Studies

- Monitor studies on the FIRST concept concerning antenna accuracy, space deployment, pointing and surface stabilisation.
- Formulate a detailed set of requirements for further study of the antenna.

Instrument Studies

- Analyse requirements for on-board frequency stability to establish whether an on-board hydrogen maser is mandatory.
- Monitor space-agency and commercial developments in very wideband data transmission.
- Study the use of cryogenic technology developed within ESA for cooling the mm VLBI receivers.

Optical Interferometry – Two-Dimensional Aperture Synthesis

Mirror and Configuration Studies

- Study techniques of replicating mirrors with the same optical figure.
- Design study of optical system.
- Analyse the thermal distortion and vibration spectrum of the rigid two-dimensional structure, and the differential effects of gravity on such a structure in low earth orbit.

Instrument Studies

- Design study of hardware associated with redundant calibration of the interferometer phase.
- Study on-board computing requirements for redundant calibration, and correlation.

Optical Interferometry – Two-Element Michelson Interferometer

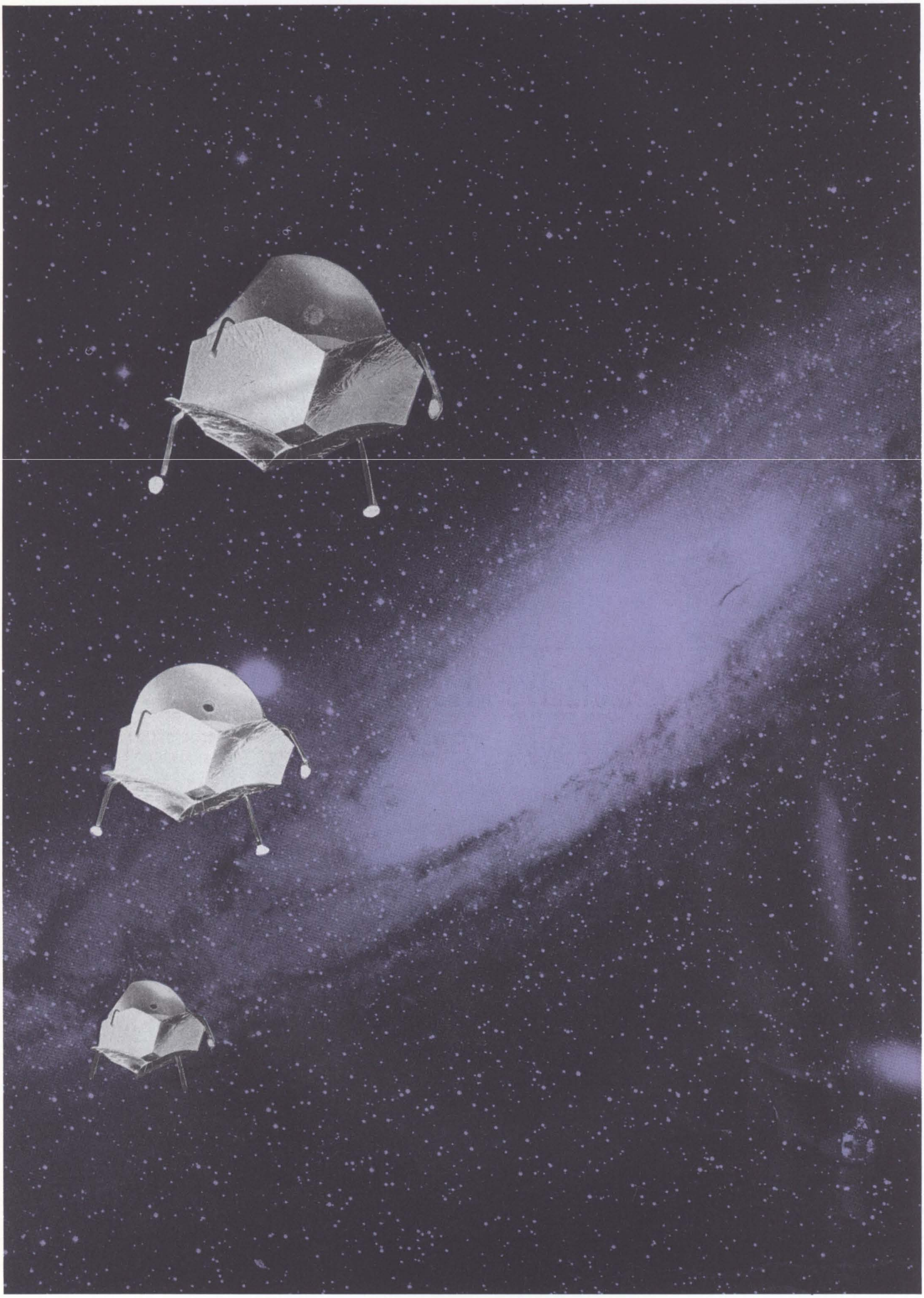
Optical System Studies

- Design study of the optical system, including mirrors and interferometer optics.

Configuration Studies

- Study of the interferometer configuration, the means of moving the elements to new spacings, and measurement techniques to determine the spacings.
- Simulation studies of the control and stabilisation of the interferometer.

Part 4. - Mission Trends
- Industrial Benefits



14. Trend Analysis of Mission Concepts – ESA Executive

As stated elsewhere some 70 proposals for mission concepts were received from the European scientific community. The level of detail of the individual proposals varied widely, ranging from very interesting ideas expressed on a single sheet of paper to detailed instrument proposals including engineering drawings.

Notwith standing this range of detail each proposals was analysed and the technical implications for each potential mission were assessed.

This chapter outlines the trends in both astronomy and solar system science, which emerged from the analysis, but does not comment on individual concepts. A listing of all responses received is given in Annex 1. The mission concepts addressing Earth sciences (atmospheric physics, climate research and solid Earth physics) were not considered, as they do not fall within the current terms of reference of the ESA space science programme.

In general it can be said that both in astronomy and solar system science there is a significant trend toward more complex, hence more expensive, missions, which places new demands on the development of instrument and spacecraft technologies.

A look beyond 2000 AD Artist's impression of an optical interferometry mission

14.1 Astronomy

Of the total number of 31 Mission concepts received in astronomy it is significant to note that about 50% were related to high energy astrophysics. Of the remainder the majority is related to UV and optical astronomy. This is not surprising in view of the long history of these disciplines in space astronomy.

In particular, in *high energy astrophysics* a large number of PI-type experiments in the fields of gamma- and X-ray imaging, spectroscopy, time variability and plasma diagnostic studies have been proposed.

Examples are Bragg crystal spectrometers, phoswich detectors, drift chambers, position sensitive gas scintillators etc., all of which could be flown on a standard low Earth orbiting carrier such as Eureca.

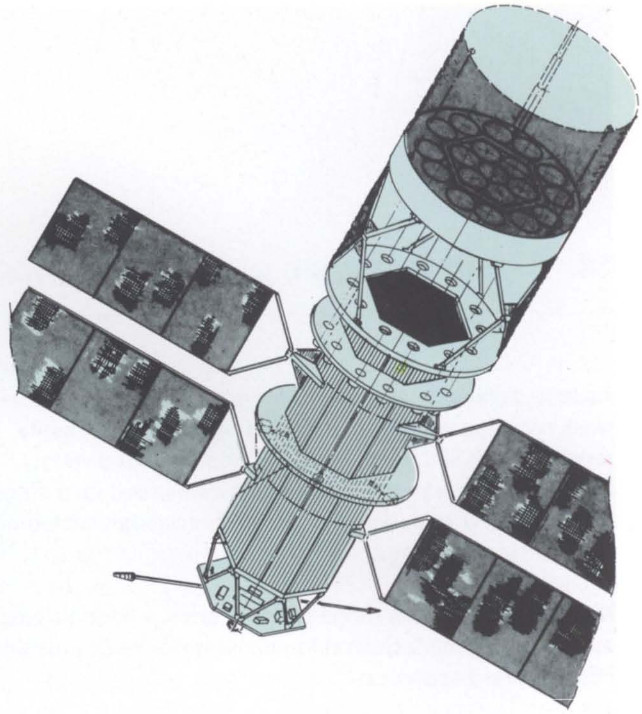
In *UV, optical astronomy* the trend is towards observatory-class missions in UV spectroscopy and wide field imaging complementary to the Space Telescope. Several specific experiments proposed address very accurate stellar spectrophotometry and UV background spectroscopy.

All of these specific experiments are fully justified scientifically, but they are, however, too narrowly defined to merit the development of a dedicated satellite. Some of them could well be flown as additional instruments on a large observatory, others could benefit from the availability of a standard platform such as Eureca and/or Space Station.

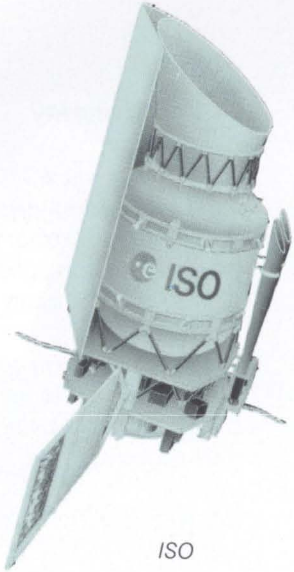
Infrared, sub-millimetre and radio astronomy are very young disciplines in space research. In infrared astronomy the results of the NL-UK-US satellite IRAS are being analysed and will certainly lead to a need for more detailed studies of specific phenomena. The nature and scope of the necessary instrumentation is at present difficult to foresee. So far, the Infrared Space Observatory (ISO) is the most obvious and eagerly awaited successor to the IRAS mission. The European development of cryogenic technology related to the ISO mission will provide the basis for continuing emphasis in the infrared and submillimetre disciplines.

In *radio astronomy* the need for large baselines can only be satisfied by making the step into space. This step implies that the techniques presently used for ground based radio astronomy should be implemented in th3 space environment. For example, large high accuracy antennas in the centimetre and millimetre bands, wide-bandwidth receivers and data transmission techniques are required.

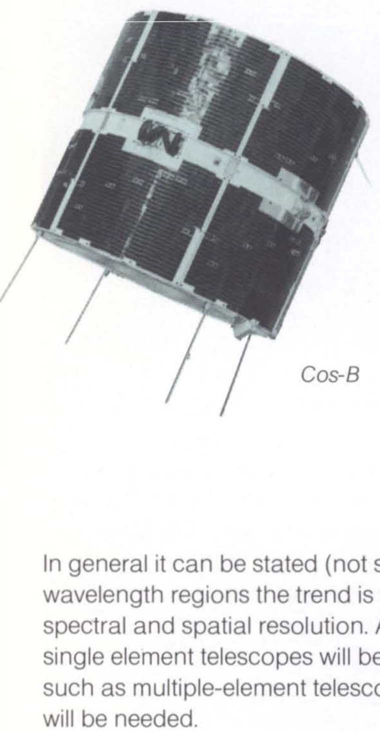
The growing complexity of astronomy missions



XMM



ISO



Cos-B

In general it can be stated (not surprisingly) that in all wavelength regions the trend is towards increased sensitivity, spectral and spatial resolution. As a result the capabilities of single element telescopes will be exceeded and new techniques such as multiple-element telescopes and interferometric arrays will be needed.

14.2 Solar System Science

Since the earliest days of space research in Europe investigations in solar system science have been conditioned by the availability of launching systems. The availability of American Scout and Delta launchers on a cooperative or cost-reimbursement basis made accessible the near-Earth region of space in which studies of ionospheric and magnetospheric physics were conducted. More powerful launchers were also available in the USA but at greater cost. As a result, until the European Ariane rocket became available, only one deep-space mission was undertaken by ESA, namely, Ulysses (ISPM) in which the cost of the Shuttle/Centaur launcher is borne by NASA as part of a collaborative venture. Giotto, will be the first European deep-space mission to be launched by an Ariane-I rocket.

Many of the mission concepts analysed here exploit the capability of the Ariane family of rockets to launch deep-space missions. Some require the full capability of the most powerfull Ariane-IV and some require, in addition, the use of gravity assist techniques using Venus or Jupiter swing-bys or the use of a low thrust solar-electric propulsion system.

The most ambitious *deep-space missions* make new demands on spacecraft technology in one or more of the following areas:

- thermal control for extremes of solar irradiance
- rendezvous with and landing on celestial objects. This must be automated because of the great distances from Earth
- sample collection, e.g., dust capture, boring
- sample return
- power generation: advanced solar arrays or RTG's.

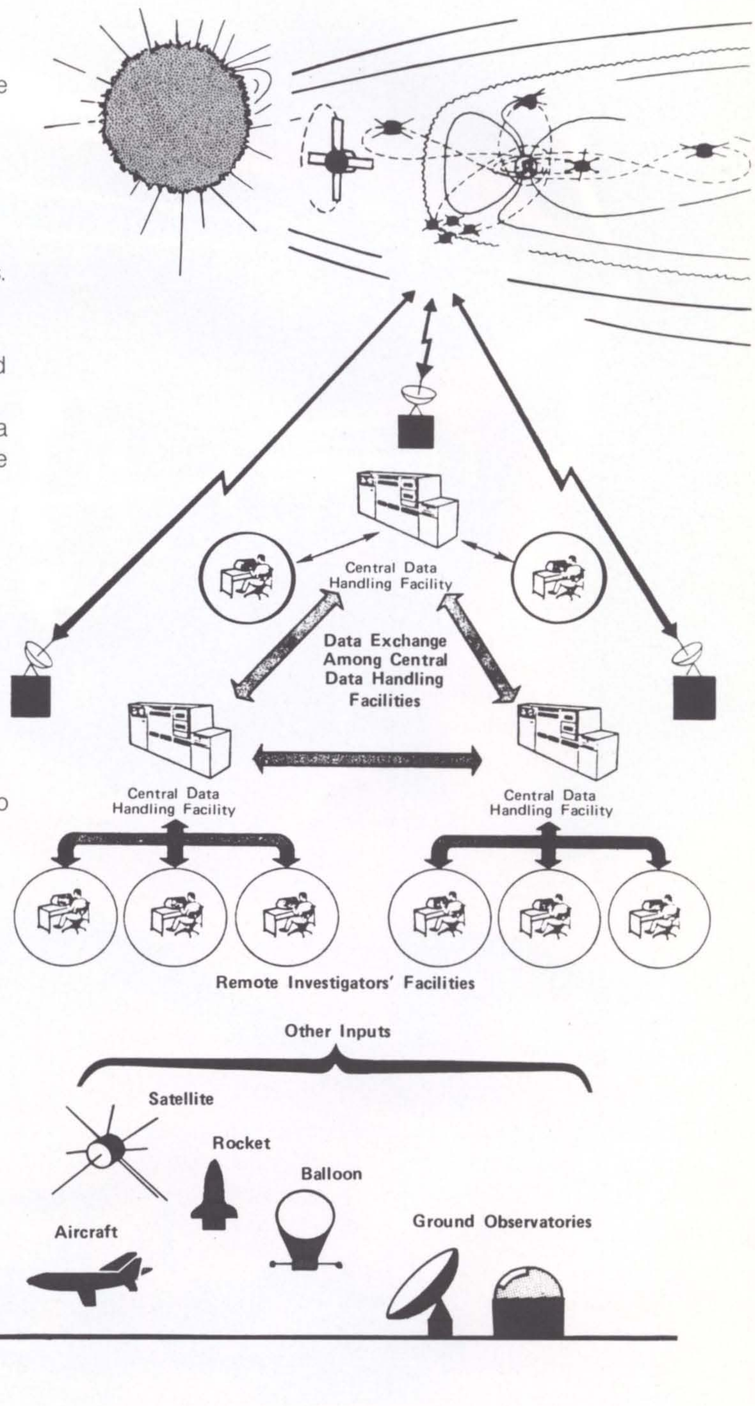
Planetary science, for example the study of Mercury, asteroids and comets, is the main driver behind these missions, although some aspects of solar and heliospheric physics, gravitational physics and interstellar physics would also benefit from such advanced technology (e.g. by means of a heliosynchronous solar orbiter).

Not all deep-space mission concepts require the biggest launchers and the most advanced technology. Some missions have been conceived deliberately to be within the current state-of-the-art. This group includes missions to Mars, Venus, the Moon, and some cometary and radio-science missions. In one case the re-use of an existing spacecraft concept (Giotto) is proposed.

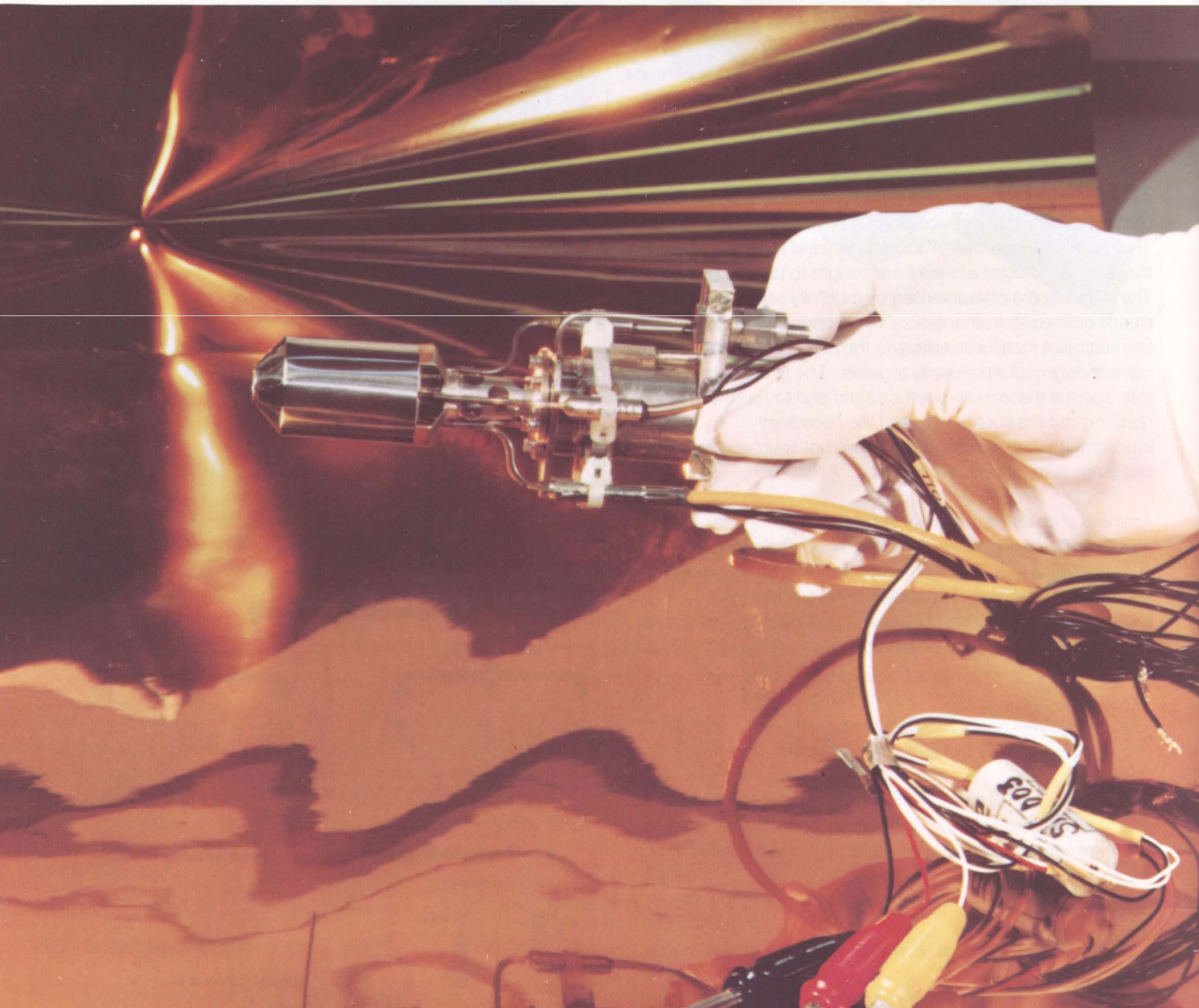
While some of the deep-space missions which are envisaged can be adequately served by existing or planned European tracking and data acquisition facilities, some require a genuine deep-space network, and all would benefit from an improved capability in this critical area.

Near-Earth missions make up slightly more than half the mission concepts considered under solar system science. The disciplines served are space plasma physics and solar physics. These are mature areas of science, beyond the exploratory stage, where precise answers are sought to precise questions. The missions are characterised by carefully selected orbits and clearly defined instrumentation. Two trends emerge: the need for multipoint measurements and the need to handle high data rates, though not necessarily together. The technical challenge is to operate these multi-point systems and to handle the resulting data in such a way that the necessary intercomparisons can be made. While not spectacular, this challenge is real and must be met.

Ariane is seen as the principal launch vehicle for near-Earth missions. There are cases, however, where the specific characteristics of a Shuttle-launched platform may be useful Examples are the use of Spacelab for active plasma experiments and the use of Eureca for a limited range of solar physics investigations. A programme of sounding rocket is also proposed.



The science data systems of the future as exemplified by the ISTP programme



The 2-N thruster for use on board ISPM spacecraft. (Photo ERNO, Bremen).

15. Industrial Benefits Derived from the European Space Science Programmes – ESA Executive

Industry has a crucial part to play in any future plan for European Space Science, both at the European and National level. A number of industrial concerns were approached, and asked to give some indication of the benefits they thought had accrued from participation in Scientific satellite projects. Of particular interest was an assessment of the access to developments and markets which might otherwise not have happened.

Replies came from a sufficiently wide selection of firms and countries to be indicative of trends across Europe. In all cases the responses were positive, and one may draw the conclusion that European Industry is ready and eager for the challenge of new Scientific projects.

15.1 Developments for Scientific Activities which have been of Direct Benefit to Other Space Programmes

Much depended on the type of work undertaken, but a point of general interest was made that scientific spacecraft had been important to the space industry because they advanced the technology and broadened the skill base. The reason given was the scientists' insistence on having the latest technology possible, and accepting the risks inherent in such a philosophy.

Those firms dealing with data handling reported that their sub-systems had been adapted, or formed the basis of units for other scientific and application satellites. The same was true for attitude control systems. One firm reported that its work on three axes stabilised systems had been successfully transferred to application programmes at both national and international level. Equally power supply and storage systems, momentum wheel technology and simulation techniques had been developed for scientific satellites and then adapted for application programmes. A number of technological achievements were used on other programmes including lightweight and other materials, tribology, and optical measuring technology. Development of the D-mirror for the Halley multicolour camera on-board Giotto had been of prime importance for the production of astronomical mirrors.

Of interest was the statement by a prime contractor that the evolution of model philosophy and the development of quality assurance skills, had led to major reductions in programme costs. The original five-model sequence was typically, structural model, thermal model, engineering model, qualification model, flight model, and possibly a complete spare flight model. Confidence has enabled prime contractors to reduce to a three-model sequence, typically, structural model, electrical model (less complete than the engineering model), protoflight model and spares of a few critical pieces of equipment, without loss of reliability.

One negative, but relevant comment concerns ESA's geographical distribution policy. It was pointed out that this policy may prevent firms with mature systems from being able to use them on other ESA projects. There were comments too, that lack of a balanced science programme can have adverse effects on continuity of work in industries which cater for such programmes.

15.2 Development of Products, not necessarily for Space Application, stemming from work performed for the Scientific Programme

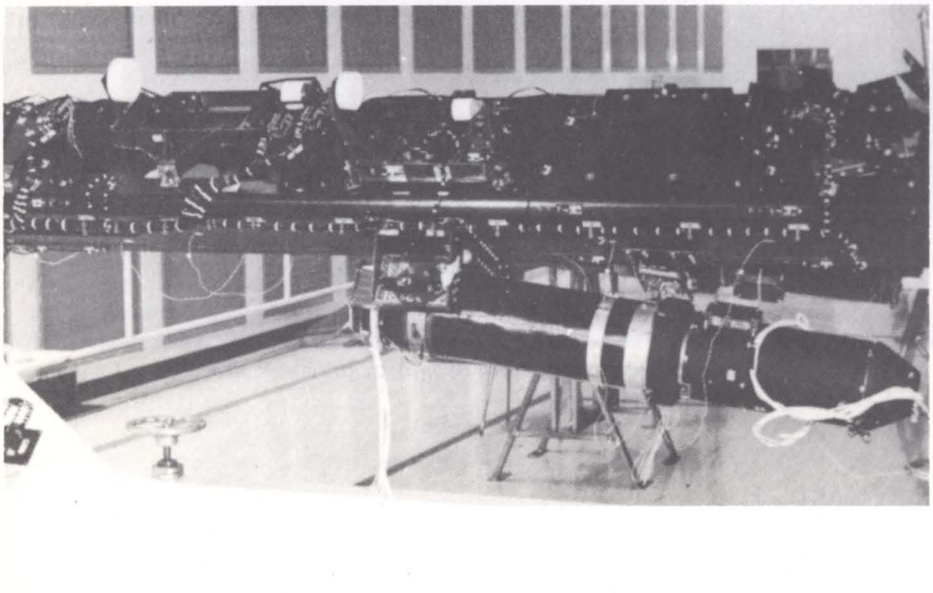
Those firms set up specially for space work were at a disadvantage in answering this question. Others gave examples illustrating the wide range of subjects and equipment which have led to other contracts and developments. PCM switching system, process control computer systems, earth stations were mentioned. Arising from work done on scientific satellites, one firm has developed control and automation systems for use in metro underground railways, in nuclear-reactor plants, and car assembly lines. Such work could be of considerable importance when in-orbit infrastructure systems are developed. Front-end hybrid amplifiers for high energy physics application have gone to universities and institutes in five countries, including several in the USA. Telemetry, telecommand and data processing have been adapted to marine use for submarine robots and meteo-oceanographic buoys. Assembly and test facilities have been used for non-space products with excellent results. Various technological advances have been used for other products including bonding techniques, carbon fibre applications. The advances in manufacturing 'know-how' have led to indirect improvements in production of many non-space related activities.

15.3 Improvements to Products or Activities through Methods Developed by the Scientific Programme, whether Technological or Managerial

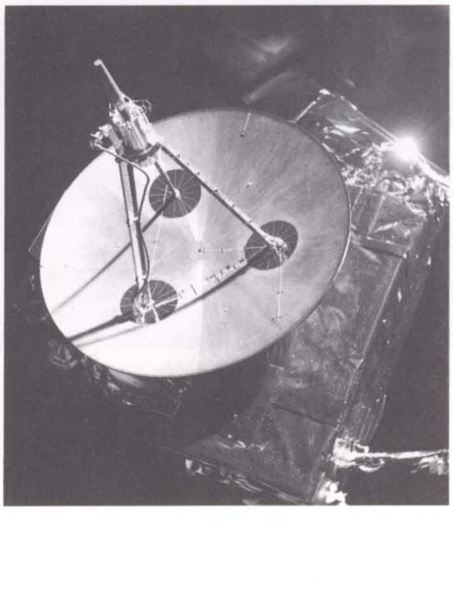
Firms spoke particularly of managerial skills being passed on from the Science projects to others, and various design and test methodologies being adapted for other products. One firm cites, as a prime example, that the management organisation it developed for a major scientific satellite has been successfully adapted for application satellites, and other management tasks outside space-work, including setting up a metro system. Work on composite materials for the Faint Object Camera has directly benefited the HRV instrument for SPOT. Antennas are being manufactured from kevlar. The development of bonding technology for satellite structures has provided a sound basis for continuous commercial activities in lightweight products and engineering. Carbon fibre applications for struts and other structural elements have led to diversified application in industries, the stringent requirements of which can be met by this technology.

Examples of composite materials in use.

FOC structural model .



ISPM carbon fibre dish antenna (2 m).



Internationalism at work.

15.4 Access to International Markets

Again there were widely differing examples, some of which have already appeared above. An interesting example was the delivery of a complete network to monitor radioactive fall-out on food. Other international customers, including Intelsat, Inmarsat, Arabsat, Insat, JET, CERN, have recognised the quality of work done on ESA's scientific satellites and national programmes have been prepared to buy 'foreign' proven products. Consultancies have been established to serve other areas advancing into high-technology including the medical profession.

15.5 Economic Growth

There has been an understandable difficulty for firms to isolate growth factors attributable to the scientific programme. All agree that considerable growth has taken place, both in financial terms and in most cases, in a steady increase in the labour force.

15.6 Conclusions

The innovative nature of Scientific Satellite Projects is seen by Industry as a technical spur which drives them to think up new concepts, new methods, and new instruments. These, once proven, are used to give those industries an edge when competing in other markets.

There is a very clear impression that Industry looks forward to the exciting challenges to be offered by a comprehensive long-term European Space Science Programme.

A modern check-out system, developed mainly for scientific satellites but having a much wider application.

Annexes

Annex I

Responses to Call for Mission Concepts: Solar System

Author	Affiliation	Title
H. Fechtig E. Grün	Max Planck Institut für Kernphysik Heidelberg (D)	In-situ measurements of the instellar medium
R.W.P. McWhirter	Rutherford Appleton Laboratory, Chilton (UK)	Solar coronal heating and solar flare mechanisms
W.H. Ip K. Jockers H.U. Keller A. Korth G. Kremser H. Rosenbauer W. Stüdemann B. Wilken H. Fechtig E. Grün H. Jessberger J. Kissel D. Krankowsky P. Lämmerzahl H. Völk H. Balsiger F. Bühler P. Eberhardt J. Geiss	Max Planck Institut für Aeronomie, Lindau (D) Max Planck Institut für Kernphysik, Heidelberg (D) Physikalisches Institut, Bern (CH)	Comets-90: A comprehensive cometary research programme
D.A. Bryant	Rutherford Appleton Laboratory, Chilton (UK)	10-year rocket programme in basic plasma physics
F.W. Taylor	Dept. of Atmospheric Physics, Oxford (UK)	Mars dual orbiter
A.K. Richter W.I. Axford A. Brahic M. Coradini W. Kokott H. Wänke A. Balogh C. Chiuderi H. Fechtig F.M. Neubauer G. Wibberenz	Max Planck Institut für Aeronomie, Lindau (D) University of Victoria, Wellington (NZ) Observatoire de Paris, Meudon (F) Istituto di Astrofisica Spaziale, Roma (I) Messerschmitt-Bölkow-Blohm, Ottobrun (D) Max Planck Institut für Chemie, Mainz (D) Imperial College of Science and Technology London (UK) Osservatorio Astrofisico di Arcetri, Firenze (I) Max Planck Institut für Kernphysik, Heidelberg (D) Institut für Geophysik und Meteorologie, Köln (D) Institut für Reine und Angewandte Kernphysik Kiel (D)	Mercury and asteroid fly-by–solar synchronous mission
P. Maltby	Institute of Theoretical Astrophysics, Oslo (N)	Eurasol: Eureca mission dedicated to solar physics

M.K. Bird H. Volland P. Edenhofer H. Porsche	Radioastronomisches Institut, Bonn (D) Institut für HF-Technik, Bochum (D) Deutsche Forschungs- und Versuchsanstalt für Luft und Raumfahrt, Oberpfaffenhofen (D)	SOS: Solar Occulted Station
A.H. Gabriel	Rutherford Appleton Laboratory, Chilton (UK)	Missions based on Soho concepts
A.H. Gabriel	Rutherford Appleton Laboratory, Chilton (UK)	Heating of the solar atmosphere
P. Eberhardt	Physikalisches Institut, Bern (CH)	Re-examination of earlier proposals, including Polo and Kepler
P. Eberhardt	Physikalisches Institut, Bern (CH)	Further cometary missions
C.C. Harvey	Observatoire de Paris, Meudon (F)	In-ecliptic support of ISPM using available hardware
B. Hultqvist C.-G. Fälthammar R. Boström	Kiruna Geophysical Institute, Kiruna (S) Institute of Plasma Physics, Stockholm (S) Uppsala Ionospheric Observatory, Uppsala (S)	Magnetospheric/Ionospheric Fine Structure Missions
R. Boström C.G. Fälthammar B. Hultqvist	Uppsala Ionospheric Observatory, Uppsala (S) Institute of Plasma Physics, Stockholm (S) Kiruna Geophysical Institute, Kiruna (S)	Missions for Active Space Plasma Experiments
A. Balogh A.K. Richter	Imperial College of Science and Technology London (UK) Max Planck Institut für Aeronomie, Lindau (D)	Solar Synchronous Orbiter
P. Bruston	Laboratoire de Physique Stellaire et Planétaire, Verrières (F)	Spring: Synoptic Planetary Research with an Imaging Normal Grating
R. Lundin B. Hultqvist	Kiruna Geophysical Institute, Kiruna (S)	Plasma mantle mission
D. Jones	Space Plasma Physics, Cambridge (UK)	Main: Magnetosphere-Atmosphere Interactions
V. Formisano A. Coradini M. Fulchignoni E. Flamini C. Federico	Istituto di Fisica dello Spazio Interplanetario Frascati (I) Istituto Astrofisica Spaziale, Frascati (I) University of Sussex, Brighton (UK) Università di Perugia, Perugia (I)	Selene: A mission to the Moon
A.K. Richter M. Coradini	Max Planck Institut für Aeronomie, Lindau (D) Istituto di Astrofisica Spaziale, Roma (I)	Mercury orbiter mission: Hermes
C.-G. Falthammar B. Hultqvist R. Boström	Institute of Plasma Physics, Stockholm (S) Kiruna Geophysical Institute, Kiruna (S) Uppsala Ionospheric Observatory, Uppsala (S)	Use of ejectable probes for field, plasma and wave investigations
S.J. Bauer W.H. Ip	Institut für Meteorologie und Geophysik, Graz (A) Max Planck Institut für Aeronomie, Lindau (D)	Multiple Venus orbiters: Venture
A.D. Johnstone A.J. Coates	Mullard Space Science Laboratory, Dorking (UK)	Multi spacecraft mission for low-to-medium altitude auroral studies
J.A.M. McDonnell	University of Kent, Canterbury (UK)	Comex: Cometary exploration by in-situ sampling analysis and imaging reconnaissance
R. Rummel	Technische Hogeschool, Delft (NL)	Gradiometric satellite mission

A. Pedersen	SSD/ESA	Shuttle pallets for atmospheric and plasma physics
J.P. Delaboudinière M. Malinovsky P. Lemaire	Laboratoire de Physique Stellaire et Planétaire, Verrières (F)	Solar physics investigations using Eureca
D. Llewellyn-Jones	Rutherford Appleton Laboratory, Chilton (UK)	Atmospheric Composition and Dynamics Mission
D.L. Croom	Rutherford Appleton Laboratory, Chilton (UK)	Atmospheric Wind Profile Satellite (AWPS)
D.L. Croom	Rutherford Appleton Laboratory, Chilton (UK)	Advanced Microwave/Infrared Sounding Unit (AMIRSU)
J. Kissel	Max Planck Institut für Kernphysik, Heidelberg (D)	Giotto-II
S.M.P. McKenna-Lawlor	Experimental Physics Department, Maynooth (IRE)	Solar Radio Astronomy from Space
A.E. Kingston	Queen's University, Belfast (UK)	Solar Atomic Physics
B. Bertotti	Dipartimento di Fisica Nucleare e Teorica Pavia (I)	Geophysical Hipparcos Low Frequency Gravitational Wave Detector by means of Doppler Measurements Precise Measurement of the Gravitational Field of the Sun by means of a Mercury Orbiter

Responses to Call for Mission Concepts: Astronomy

Author	Affiliation	Title
D. Ramsden	Rutherford Appleton Laboratory, Chilton (UK)	An imaging telescope for high energy gamma-ray astronomy
J.J. Quenby A.R. Engel G.K. Rochester P. Sanford	Blackett Laboratory, London (UK) University College, London (UK)	Cosmic X-ray Spectroscopy
N. Lund	Danish Space Research Institute, Lyngby (DK)	Hard X-ray positron annihilation line astronomy
A.J. Dean G. di Cocco P. Ubertini G. Villa G. Simnett A. Engel	Department of Physics, Southampton (UK) Istituto TESRE-CNR, Bologna (I) Istituto Astrofisica Spaziale, Frascati (I) Istituto di Fisica Cosmica, Milano (I) Space Science Department, Birmingham (UK) Imperial College of Science and Technology London (UK)	Low energy gamma-ray imaging satellite
P. Biermann	Max Planck Institut für Radioastronomie, Bonn (D)	High-energy X-ray imaging telescope
P. Biermann	Max Planck Institut für Radioastronomie, Bonn (D)	A wide field gamma-ray telescope
H.W. Schnopper	Danish Space Research Institute, Lyngby (DK)	XMM – the X-ray multi-mirror
K.A. van der Hucht	Astronomical Institute, Utrecht (NL)	UV Schmidt survey
R.M. West M. Golay	European Southern Observatory, Garching (D) Observatoire de Genève, Genève (CH)	Space Schmidt – a fast wide angle telescope

J. Trümper	Max Planck Institut für Physik und Astrophysik, Garching (D)	Spextel: Spectroscopic X-Ray Telescope Mission
R. Staubert P. Ubertini J.F. Spada	Astronomisches Institut, Tübingen (D) Istituto Astrofisica Spaziale, Frascati (I) Istituto TESRE-CNR, Bologna (I)	Isphax: Imaging Spectro-Photometric Hard X-ray Mission
J.C. Pecker	Collège de France, Paris (F)	Out-of-ecliptic space telescope
G. Winnewisser	Physikalisches Institut, Köln (D)	FIRST – A far infrared and sub-millimeter space telescope
R.T. Schilizzi	Radiosterrenwacht, Dwingeloo (NL)	Quasat – a VLBI observatory in space
R.T. Schilizzi R.S. Booth M.S. Longair I.I.K. Pauliny-Toth P.N. Wilkinson B.F. Burke R.A. Preston A.C.S. Readhead N.S. Kardashev	Radiosterrenwacht, Dwingeloo (NL) Onsala Space Observatory, Onsala (S) Royal Observatory, Edinburgh (UK) Max Planck Institut für Radioastronomie, Bonn (D) Nuffield Radio Astronomy Laboratories Jodrell Bank (UK) Massachusetts Institute of Technology Cambridge (USA) Jet Propulsion Laboratory, Pasadena (USA) California Institute of Technology, Pasadena (USA) Space Research Institute, Moscow (USSR)	Millimeter VLBI: High Angular Resolution Space Astronomy
A. Mangeney F. Praderie P. Lemaire	Observatoire de Paris, Meudon (F) Laboratoire de Physique Stellaire et Planétaire Verrières (F)	Stellar seismology studies
W.M. Burton	Rutherford Appleton Laboratory, Chilton (UK)	UVISAT – ultraviolet imaging and spectroscopy astronomical telescope
R. Rocchia L. Koch-Miramond H. Schnopper E. Silver P. de Korte J.L. Culhane A.C. Brinkman B.G. Taylor	Service d'Astrophysique, Saclay (F) Danish Space Research Institute, Lyngby (DK) Leiden University, Leiden (NL) Mullard Space Science Laboratory, Dorking (UK) Utrecht University, Utrecht (NL) Space Science Department, European Space Agency	Corona – an all sky X-ray spectroscopic survey of the hot interstellar medium
J.M. Deharveng M. Joubert	Laboratoire d'Astronomie Spatiale, Marseilles	CUBE – Cosmic Ultraviolet Background Experiment
P.A.J. de Korte	Laboratory for Space Research, Leiden (NL)	EXUV – spectroscopy mission
A. Labeyrie	Centre d'Etudes et de Recherches Géodynamiques et Astronomiques, Caussols (F)	TRIO – optical interferometer in space
C. de Jager	Laboratory for Space Research, Utrecht (NL)	Carina – internal structure of giant stars
D.R. Whitehouse A.M. Cruise	Mullard Space Science Laboratory, Dorking (UK)	HTS – the High Throughput Spectrometer
R. Wilson	University College, Longdon (UK)	Columbus – ultraviolet astronomy mission
L. Scarsi G. Manzo M. Morini B. Sacco G. Boella	Istituto di Fisica Cosmica, Palermo (I) Istituto di Fisica Cosmica, Milano (I)	Broad band X-ray spectrometer

M. Morini	Istituto di Fisica Cosmica, Palermo (I)	X-ray transient and bright source variability monitor
R. Gispert J.M. Lamarre G. Chambon G. Serra M. Combes J.L. Puget D. Rouan J.P. Torre	Laboratoire de Physique Stellaire et Planétaire, Verrières (F) C.E.S.R. Toulouse (F) D.E.S.P.A., Meudon (F) E.N.S., Paris (F) L.A.I.R., Meudon (F) Service d'Aéronomie, Verrières (F)	SMIT – sub-millimeter telescope
A. Peacock A. Smith	SSD/ESA	Survey of galactic plane
G. Spada F. Frontera L. Scarsi G. Manzo N. Robba E. Costa	Istituto TESRE-CNR, Bologna (I) Istituto IFACI-CNR, Palermo (I) Istituto di Fisica, Palermo (I) Istituto IAS-CNR, Frascati (I)	Haxtel – Hard X-ray telescope
J. Noordam	Netherlands Foundation for Radio Astronomy Dwingeloo (NL)	OASIS: A multi-element telescope for optical aperture synthesis in space

Responses to Call for Mission Concepts: Miscellaneous

Author	Affiliation	Title
R.J. van Duinen	Naarden (NL)	Comments on efficiency
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J. Lizon-Tati	European Space Agency/ESTEC	CHRESUS: liquid helium cryostat facility
E. Bussoletti	Dipartimento di Fisica, Lecce (I)	Support to Comex
H.C. v.d. Hulst	Sterrewacht, Leiden (NL)	Comments on various aspects
J. van Paradys	Astronomical Institute 'A. Pannehoek' Amsterdam (NL)	Comments on X-ray missions
P. Clegg	Queen Mary College, London (UK)	Comments on infrared missions

Some of the contributors photographed during the Survey Committee meeting held in Venice, June 1984.
(Courtesy - H.W. Schnopper).

Annex II

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