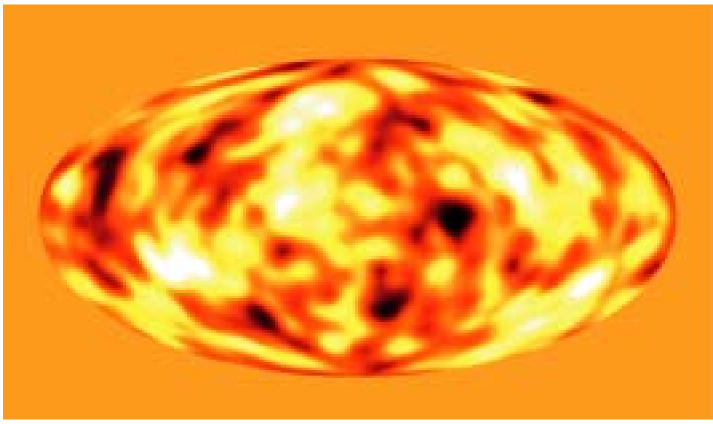
Planck

Planned achievements: most detailed observations to date of Cosmic Microwave Background
Launch date: planned for February 2007 (with Herschel)
Mission end: after 15 months of observations
Launch vehicle/site: Ariane-5 from Kourou, French Guiana
Launch mass: about 1430 kg (445 kg science payload)
Orbit: planned Lissajous orbit around L2 Lagrangian point, 1.5 million km from Earth in anti-Sun direction. 4-month transfer from Earth
Principal contractors: Alcatel Space Industries (prime, Payload Module, AIV), Alenia Spazio (Service Module). Phase-B April 2001 - June 2002; Phase-C/D July 2002 - September 2006, CDR November 2003

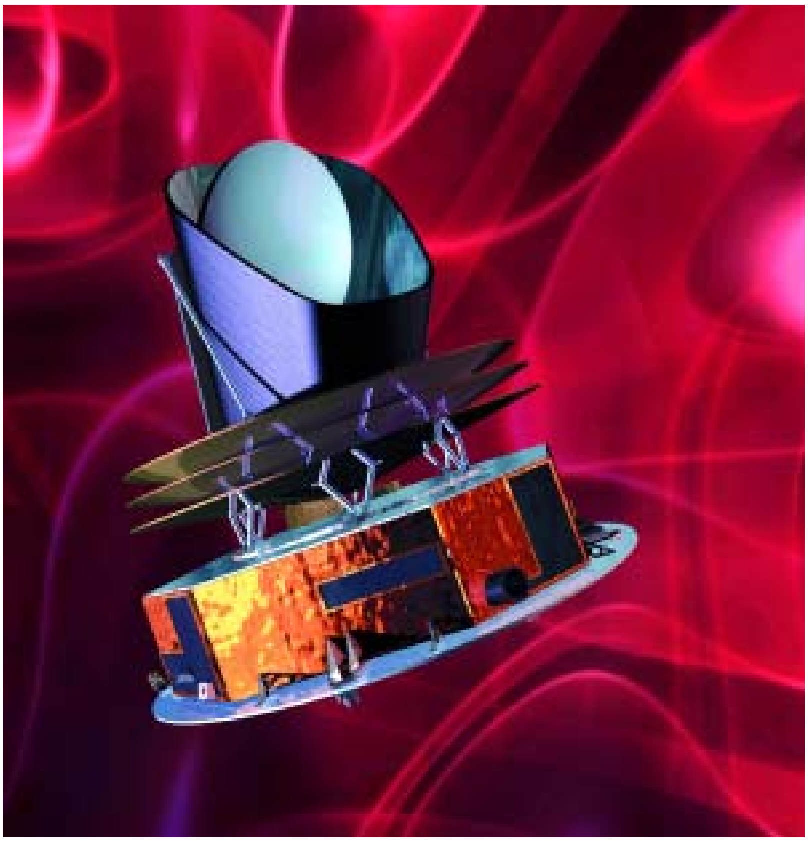
Planck is designed to help answer key questions: how did the Universe come to be and how will it evolve? To do this, it will map with the highest accuracy yet the first light that filled the Universe after the Big Bang. Its telescope will focus radiation from the sky onto two arrays of highly sensitive radio detectors. Together, they will measure the temperature of the Cosmic Microwave Background (CMB) radiation over the whole sky, searching for regions slightly warmer or colder than the average 2.73 K.

300 000 years after the Big Bang, the Universe was 1000 times smaller than now and had cooled to 3000 K. This was cold enough for hydrogen atoms to form, so light and matter now existed independently and light could travel freely for the first time. CMB radiation is that 'first light', a fossil light carrying information both about the past and the future of the Universe. This background glow was discovered in 1964. A thousand million years after the Big Bang, the Universe was a fifth of its present size and stars and galaxies already existed. They formed as matter accreted around primaeval dense 'clots' that were present in the early Universe and that left their imprint in the radiation, at the period when light and matter were still closely coupled. Today, the fingerprints of these clots are detected as very slight differences – sometimes as small as one in a million – in the apparent temperature of the CMB. All of the valuable information lies in the precise shape and intensity of these temperature variations. In 1992, NASA's COBE satellite made the first blurry maps of these anisotropies in the CMB. Planck will map these features as fully and accurately as possible.

The anisotropies hold the answers to many key questions in cosmology. Some refer to the past of the Universe, such as what triggered the Big Bang, and how long ago it happened. Others look deep into the future. What is the density of matter in the Universe and what is the true nature of this matter? These parameters will tell us if the Universe



Planck will provide astronomers with a window back to the early Universe.

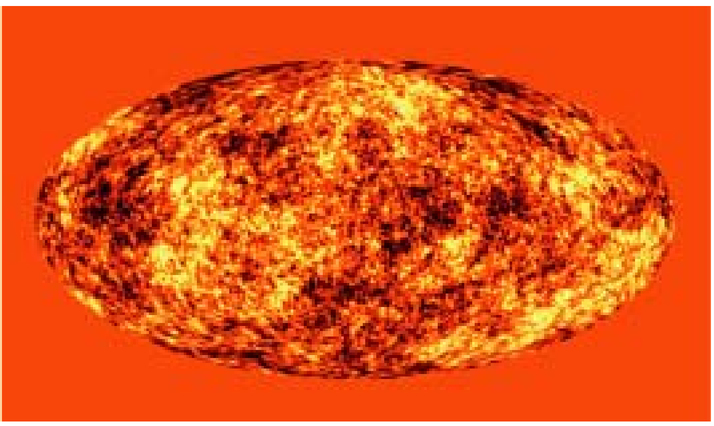


Bottom of page: simulations of observations of the CMB show the dramatic improvement that can be achieved by increasing the angular resolution from the level of the COBE satellite (left panel) to the 5-10 arcmin of Planck (right panel).

will continue its expansion forever or if it will eventually collapse on itself.

Another question is the existence of a 'dark energy' that might exist in large quantities in our Universe, as indicated by recent experiments. Is it really there? If so, what are its effects? Planck will shed light on these issues, because it will be the most powerful tool yet for analysing the CMB anisotropies.

Planck's instruments will focus on microwaves with wavelengths of 0.3 mm to 1 cm. This wide coverage solves a major challenge: to distinguish between the actual CMB and the many other undesired signals that introduce spurious noise. Many other objects, such as our own Galaxy, radiate at the same wavelengths as the CMB itself. These confusing signals have to be mapped and finally removed from the measurements. This means that many of Planck's wavelength channels are dedicated to measuring signals other than the CMB. These measurements in turn will generate a wealth of information on the dust and gas in our Galaxy and the properties of other galaxies. The Sunyaev-Zeldovich effect (a distortion of the CMB by the hot gas in galactic clusters) will be measured for thousands of clusters.



The detectors must be very cold so that their own emissions do not swamp the signal from the sky. Some will be cooled down to about 20 K and some to 0.1 K. Planck will rotate slowly and sweep a large swath of the sky each minute. In about 15 months, it will have covered the sky fully, twice over. It will operate completely autonomously and dump the stored data each day to Earth.

A call for ideas for ESA's M3 third Medium-class science mission for

Planck's scientific payload

Low Frequency Instrument (LFI)

LFI's 56 High Electron Mobility Detectors (HEMTs), fed by a ring of corrugated horns, are cooled to 20 K by H_2 sorption cooler. PI: Reno Mandolesi, Istituto di Tecnologie e Studio delle Radiazioni Extraterrestri (CNR), Bologna (I).

Centre Frequency (GHz)	30	44	70	100
Number of Detectors	4	6	12	34
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.2
Angular Resolution (arcmin)	33	23	14	10
Average $\Delta T/T$ per pixel (12 months, 1σ, 10^{-6} units)	1.6	2.4	3.6	4.3
Sensitive to linear polarisation?	yes	yes	yes	yes

High Frequency Instrument (HFI)

HFI's 50 bolometers, fed by corrugated horns and filters, are cooled to 0.1 K by a combination of a 20 K sorption cooler, a 4 K Joule-Thompson mechanical cooler and an open-cycle dilution refrigerator. PI: Jean-Loup Puget, Institut d'Astrophysique Spatiale (CNRS), Orsay (F).

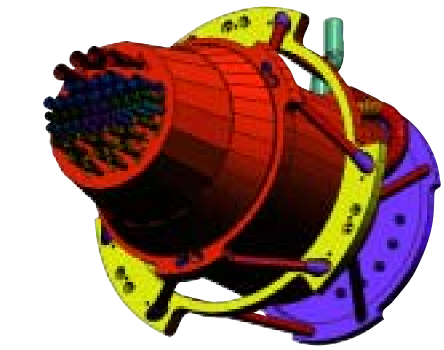
Centre Frequency (GHz)	100	143	217	353	545	857
Number of Detectors	4	12	12	6	8	6
Bandwidth ($\Delta\nu/\nu$)	0.25	0.25	0.25	0.25	0.25	0.25
Angular Resolution (arcmin)	10.7	8.0	5.5	5.0	5.0	5.0
Average $\Delta T/T$ per pixel (12 months, 1σ, 10^{-6} units)	1.7	2.0	4.3	14.4	147.0	6670
Sensitive to linear polarisation?	no	yes	yes	no	yes	no

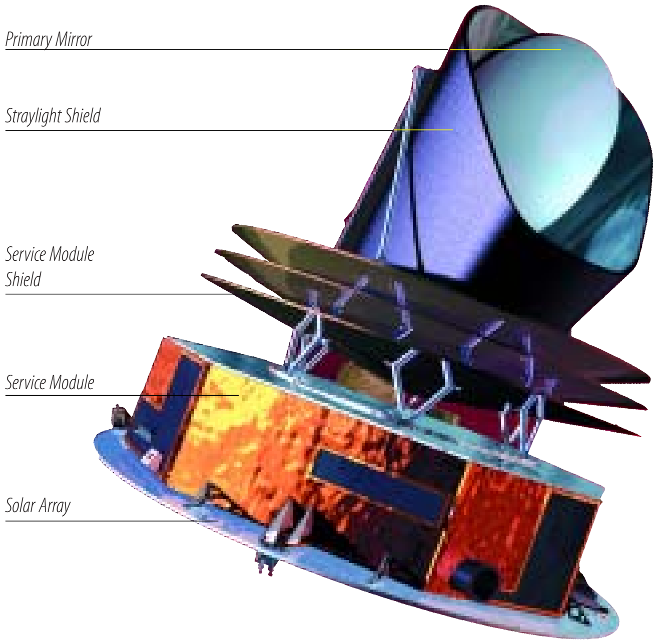
Telescope

1.5 m-diameter telescope, 8°-FOV, 1.8 m focal length, is offset by 85° from Planck's spin axis to scan the sky. Both reflectors are CFRP. LFI/HFI occupy the focal plane, with HFI's detectors in the centre surrounded by LFI's in a ring. PI: Hans Ulrik Nørgaard-Nielsen, Danish Space Research Institute. Copenhagen (DK).

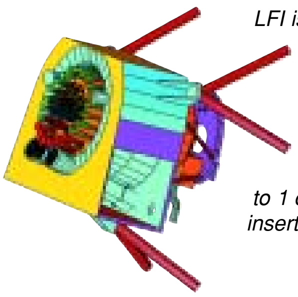
launch in 2003 was issued to the scientific community in November 1992. Assessment studies began in October 1993 on six, including what was then called COBRAS/SAMBA (Cosmic Background Radiation Anisotropy Satellite/Satellite for Measurement of Background Anisotropies, originally two separate proposals). The studies were completed in April 1994 for four to continue with Phase-A studies until April 1996. COBRAS/SAMBA was selected as M3 by ESA's Science Programme Committee in June 1996. However, the SPC in February 1996 had already ordered a reduction in the cost of new missions, so starting in 1997 several studies looked at how M3 could be implemented more cheaply. Three scenarios were considered: a dedicated satellite; a merged mission with Herschel, operating the instruments in turn; a dedicated satellite launched in tandem with Herschel. The last, 'carrier', option was selected by the SPC in May 1998 for a 2007 launch.

The Announcement of Opportunity for the instruments was made in October 1997. In September 2000, ESA issued a joint Herschel-Planck Invitation to Tender to industry for building both spacecraft. The responses were submitted by early December 2000 and Alcatel Space Industries was selected 14 March 2001 as the prime contractor for the largest space science contract yet awarded by ESA: €369 million, signed in June 2001. Phase-B began early April 2001.

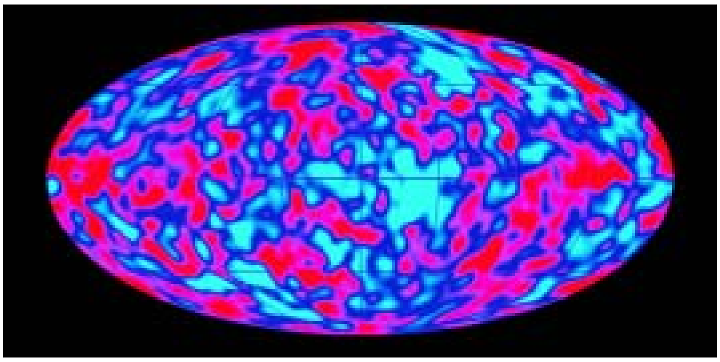




HFI is an array of 48 bolometers cooled to 0.1 K to map at six wavelengths of 0.3-3 mm.



LFI is an array of 56 tuned radio receivers using High Electron Mobility Transistors (HEMTs) cooled to 20 K to map at four wavelengths of 3 mm to 1 cm. HFI is also visible, inserted in the centre of the LFI ring of horns.



The COBE satellite in 1992 showed that the Cosmic Microwave Background varies over the sky. On scales of larger than 10°, the CMB temperature varies by about one part in 100 000 from the average 2.73 K. Planck will produce a far more detailed map.

Satellite configuration: octagonal service module with a sunshield carrying solar array. CFRP central cone, 8 CFRP shear webs, CFRP upper/lower platforms. Payload module houses telescope, two science instruments and their coolers.

Attitude/orbit control: spin-stabilised at 1 rpm about longitudinal axis to scan telescope across sky. Pointing error 16.9 arcsec. ERC 32-based attitude control computer; star mapper, 3x2-axis Sun sensors, 2x3-axis quartz rate sensors. Redundant sets of 6x10 N + 2x1 N thrusters; 3x135 kg hydrazine tanks.

Power system: solar array mounted on Earth/Sun-facing thermal shield, GaAs cells provide 1664 W EOL, supported by 2x36 Ah Li-ion batteries.

Communications: data rate 100 kbit/s 30 W X-band from single 25 Gbit solid-state recorder to ESA's Perth (Australia) station; 3-hour data dump daily. Controlled from Mission Operations Centre (MOC) at ESOC; science data provided to the two PI Data Processing Centres.

Herschel

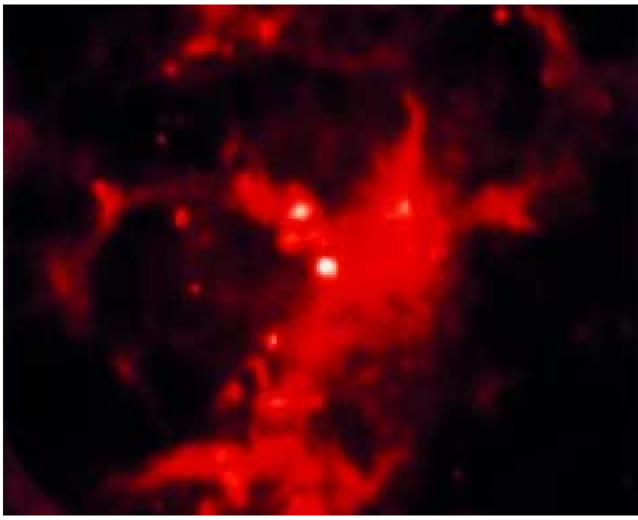
Planned achievements: first spaceborne observations at 100-600 µm, largest telescope ever launched (3.5 m diameter mirror)
Launch date: planned for February 2007 (with Planck)
Mission end: minimum of 3 years of observations
Launch vehicle/site: Ariane-5 from Kourou, French Guiana
Launch mass: about 2970 kg (science payload 415 kg)
Orbit: planned 350 000 km halo orbit around L2 Lagrangian point, 1.5 million km from Earth in anti-Sun direction. 4-month transfer from Earth
Principal contractors: Alcatel Space Industries (prime), Astrium GmbH (AIV, cryostat), Alenia Spazio (Service Module). Phase-B April 2001 - June 2002; Phase-C/D July 2002 - September 2006, CDR November 2003

ESA's Herschel Space Observatory will be the first astronomical satellite to study the cold Universe at far-infrared and submillimetre wavelengths. Its main goal is to look at the origins of stars and galaxies, reaching back to when the Universe was only a third of its present age. When and how did galaxies form? Did they all form at about the same time? Were the first galaxies like those we see now? Did the stars form first and then congregate as galaxies? As well as peering at the distant past, Herschel will also see into the hearts of today's dust clouds as they collapse to create stars and planets.

Objects at 5-50 K radiate mostly in Herschel's wavelength range of 60-670 µm, and gases between 10 K and a few hundred K have their brightest molecular and emission lines there. Broadband thermal radiation from small dust grains is the commonest continuum emission process accross this band.

The Universe was probably already dusty as the first galaxies formed and other telescopes cannot penetrate the veil. That epoch has therefore so far remained a 'dark age' for astronomers, although pioneering infrared satellites, such as ESA's Infrared Space Observatory (ISO), have helped to outline a general scenario. Sometime after the Big Bang, the first stars formed, possibly in small clusters. With time, they merged and grew, and the accumulation of matter triggered the formation of more stars. These stars produced dust, which was recycled to make more stars. By then, the first galaxies were already in place, and they also merged to form larger systems. These galactic collisions triggered an intense formation of stars in the Universe. Herschel will see the emission from dust illuminated by the first big star-bursts in the history of the Universe.

Herschel will also show us new stars forming within their thick cocoons of dust. Gravity squeezes gas and dust towards the centre, while cooling



Herschel: the main science goals

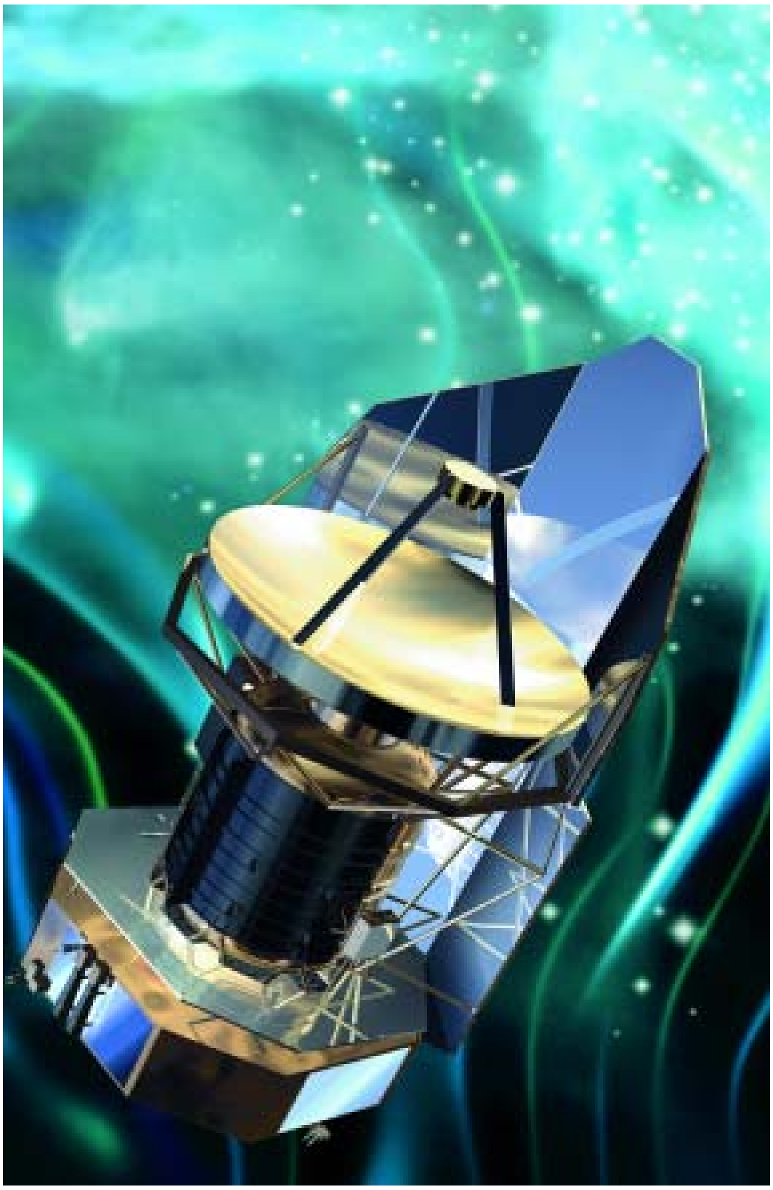
Deep extragalactic broadband photometric surveys in Herschel's 100-600 mm prime wavelength band for detailed investigation of the formation and evolution of galaxy bulges and elliptical galaxies in the first third of the age of the Universe

Follow-up spectroscopy of interesting objects discovered in the survey. The far-IR/sub-mm band contains the brightest cooling lines of interstellar gas, which provides very important information on the physical processes and energy production in galaxies

Detailed studies of the physics and chemistry of the interstellar medium in galaxies, both in our own Galaxy as well as in external galaxies, by photometric & spectroscopic surveys and detailed observations. Includes the important question of how stars form out of molecular clouds

The chemistry of gas and dust to understand the stellar/interstellar lifecycle and to investigate the physical and chemical processes involved in star formation and early stellar evolution in our Galaxy. Herschel will provide unique information on most phases of this lifecycle

High-resolution spectroscopy of comets and the atmospheres of the cold outer planets and their moons



mechanisms keep the system at very low temperatures to avoid a quick collapse and a premature death of the embryonic star. The dust cocoons and the 13 K temperatures make the pre-star cores invisible to all but radio and infrared telescopes. The earliest stages of star-birth are thus poorly known, even though ISO unveiled more than a dozen cocoons.

After starbirth, leftover gas and dust remain swirling around the young star, forming a protoplanetary disc. The dust grains are the seeds of future planets. Once the new planetary system is formed, only a thin ring of debris remains. The discs and debris rings are favourite targets for infrared space telescopes. ISO showed that planets beyond our Solar System are common. Almost all young stars are surrounded by a thin disc of debris, in which the planet-making process is not completely finished, and small bodies like comets are still very conspicuous. Herschel will shed light on all of these theories.

The Solar System was formed 4500 million years ago, out of the same raw material that about 500 million years earlier had served to build the Sun itself. To help reconstruct that formation, Herschel will study in detail the chemical composition of the planets' atmospheres and surfaces, and especially the chemical composition of comets. Comets are

Infrared-bright regions in the Trifid Nebula reveal dense clouds of cool dust that may harbour forming stars. (ESA/ISOCAM & J. Cernicharo et al.)

Herschel's scientific payload

Photodetector Array Camera & Spectrometer (PACS)

PACS is a camera and low- to medium-resolution spectrometer for 60-210 µm. Two 16×25 Ge:Ga and two bolometer detector arrays cover: 60-90 & 90-130 µm ('blue'; 3.4 arcsec pixels) and 130-210 µm ('red'; 6.8 arcsec pixels). As a photometer, images a 1.75×3.5 arcmin FOV simultaneously in 'red' and one 'blue' band. As a spectrometer, covers all three bands with 50×50 arcsec FOV, with 150-200 km^{-1} velocity resolution and instantaneous coverage of 1500 km^{-1}. PI: Albrecht Poglitsch, MPE Garching (D).

Spectral & Photometric Imaging Receiver (SPIRE)

SPIRE is an imaging photometer and low- to medium-resolution imaging Fourier Transform Spectrometer (FTS) for 200-610 µm. Both use bolometer detector arrays: three dedicated to photometry and two for spectroscopy. As a photometer, it covers a large 4×8 arcmin field of view that is imaged in three bands (centred on 250, 350, 500 µm) simultaneously. PI: M. Griffin, Queen Mary & Westfield College, London (UK).

Heterodyne Instrument for FIRST

HIFI is a heterodyne spectrometer offering very high velocity-resolution (0.3-300 km^{-1}), combined with low-noise detection using superconductor-insulator-superconductor (SIS; bands 1-5 500-1250 GHz) and hot electron bolometer (HEB; bands 6-7, 1410-1910 & 2400-2700 GHz) mixers, for a single pixel on the sky (imaging by raster mapping or continuous slow scanning). PI: Th. de Graauw, Space Research Organisation Netherlands, Groningen (NL).

the best 'fossils' of the earliest Solar System. They are made of pristine material from that primaeval cloud, including water-ice. They may also solve the question of the origin of Earth's oceans. Most of Earth's water may have come from impacting comets during the early Solar System. Herschel's spectrographs have unprecedented sensitivity to analyse the chemical composition of Solar System bodies, especially with respect to water. If cometary water has the same signature as Earth's, then the link is confirmed.

Huge amounts of water, and very complex molecules of carbon – the most basic building blocks for life – have been detected in the material surrounding stars. All living systems, including humans, are literally 'stardust'. Stars are the chemical factories of the Universe: most chemical elements are made in their cores, and many chemical compounds are produced in the stars' environments. Most molecules show their unmistakable signatures at infrared and submillimetre wavelengths, which makes Herschel an ideal tool to detect them. It will study the chemistry of many regions in the Universe, from the stars and their environments to other galaxies. It will observe objects as chemically rich as the molecular clouds in the interstellar medium, where nearly a hundred different molecules – many of which were detected in space even before they were ever seen in laboratories – have been discovered. Herschel will provide a much better understanding of the chemistry of the Universe.

Herschel's silicon carbide primary mirror will be the largest ever built for a space telescope. It is a technological challenge: it must be very light, withstand the extreme cold of space and have a surface accurate to 10^{-6} m. The infrared detectors of the three instruments must be cooler

Herschel (upper) in launch configuration with Planck (lower). (Alcatel Space)

The observatory's name, announced in December 2000, commemmorates Anglo-German astronomer William Herschel, who discovered infrared light in 1800. The mission was previously known as the Far Infrared and Submillimetre Telescope (FIRST).

than the radiation they are to measure. The telescope itself is cooled passively to 80 K, and parts of all three instruments will be kept at 1.65 K in a 2160-litre cryostat filled with superfluid helium. The SPIRE and PACS bolometer detectors will be cooled to 0.3 K. Herschel's observations will end when the cryogen is exhausted.

FIRST was one of the original four Cornerstone missions of the Horizon 2000 science plan; it was selected as Cornerstone 4 in November 1993 by the Agency's Science Programme Committee. The Announcement of Opportunity for the science instruments was released in October 1997; the SPC made its selection in May 1998. Almost 40 institutes are involved in developing the three instruments. In September 2000, ESA issued a joint Herschel-Planck Invitation to Tender to industry for building both spacecraft. The responses were submitted by early December 2000 and Alcatel Space Industries was selected 14 March 2001 as the prime contractor for the largest space science contract yet awarded by ESA: €369 million, signed in June 2001. Phase-B began early April 2001.

Satellite configuration: 9 m high, 4.5 m wide. Payload module (PLM), based on ISO's superfluid helium cryostat technology, houses the optical bench with the instrument focal plane units (SPIRE and PACS each carry an internal ^{3}He sorption cooler for 0.3 K bolometer operating temperature) and supports the telescope and some payload-associated equipment. The service module (SVM; common with Planck) below provides the infrastructure and houses the 'warm' payload equipment. Ritchey-Chretien telescope with 3.5 m-diameter CFRP segmented primary mirror with wavefront error of 6 µm, feeding Zerodur secondary. Sunshade allows mirror to cool to 80 K. The Planck mating adapter remains attached to Herschel.

Attitude/orbit control: 3-axis pointing to 2.12 arcsec. ERC 32-based attitude control; 2 star trackers, 4-axis gyro, 2x2-axis Sun sensors, 2x3-axis quartz rate sensors, 4 skewed RWs. Redundant sets of 6x10 N thrusters; 2x135 kg hydrazine tanks.

Power system: solar array mounted on thermal shield, GaAs cells provide 1450 W EOL, supported by 2x36 Ah Li-ion batteries.

Communications: data rate max. 1.5 Mbit/s (25 Gbit solid-state memory) to Perth (Australia). Controlled from Mission Operations Centre (MOC) at ESOC; science data returned to Herschel Science Centre (HSC) at Villafranca (Spain) for distribution to the three Instrument Control Centres (ICCs). The US Herschel Science Center at JPL serves US astronomers. The L2 orbit allows continuous observations and operations.

ADM-Aeolus

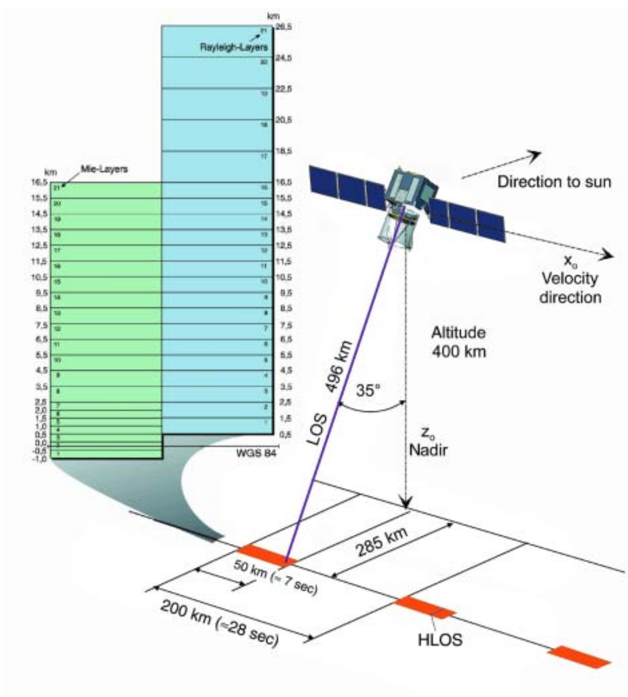
Planned achievements: the first direct global wind profile measurements throughout the atmosphere
Launch date: planned for July 2007
Mission end: after 3 years (1-year extension possible)
Launch vehicle/site: to be selected (Rockot-class)
Launch mass: about 800 kg (300 kg payload)
Orbit: planned 408 km circular, 96.99° Sun-synchronous (18:00 local time ascending node)
Principal contractors: spacecraft prime to be selected January 2002; Phase-A June 1998 - June 1999; Phase-B April 2002 - July 2003; Phase-C/D July 2003 - July 2007

The Atmospheric Dynamics Explorer (ADM) will, for the first time, directly measure wind speeds throughout the depth of the atmosphere – a notable deficiency of current observing systems. This will improve our understanding of atmospheric processes for climate studies, particularly in the tropical regions, as well as improving the numerical models used in weather forecasting. Global atmospheric transport as well as the global transfer of energy, water, aerosols and chemicals will become better understood. This more complete 3-D picture of the atmosphere will:

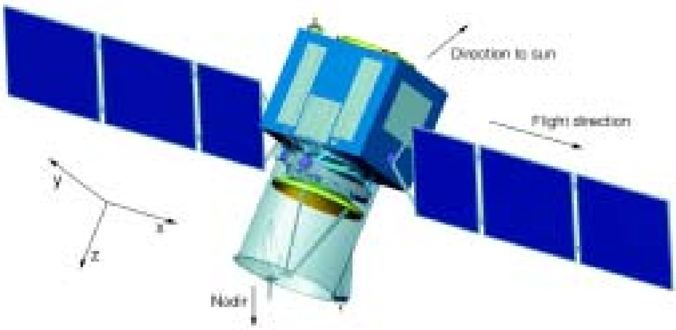
- increase the accuracy of atmospheric process parameters in models;
- advance climate and atmosphere-flow modelling;
- provide better initial conditions for weather forecasting.

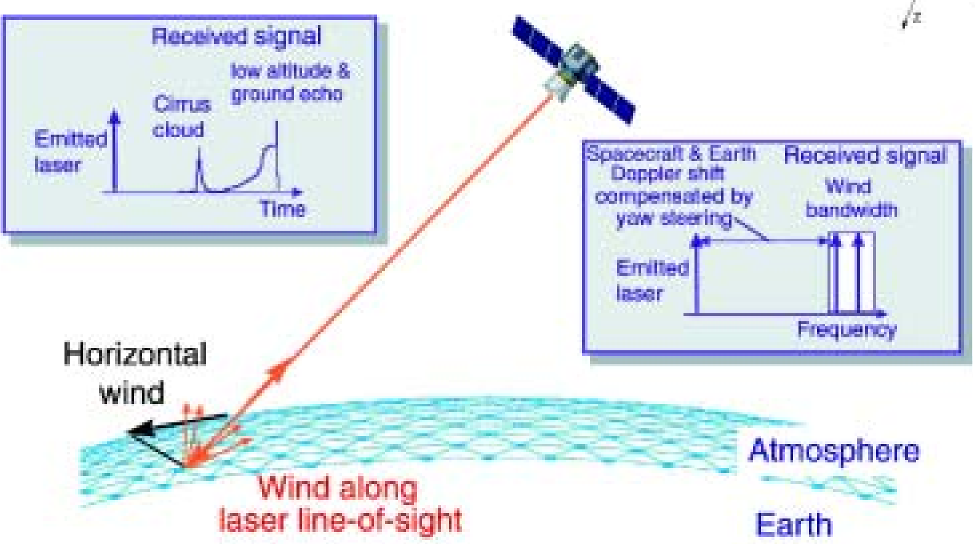
ADM was selected in 1999 as the second Earth Explorer Core mission in the Living Planet programme. Four candidate Core missions were selected in May 1996 for 12-month Phase-A studies, completed in June 1999. GOCE and ADM were selected in November 1999 for Phase-B.

The heart of ADM is the ALADIN (Atmospheric Laser Doppler Instrument) lidar emitting ultraviolet pulses. The backscatter from the atmosphere and the Earth's surface are analysed to measure cross-track wind speeds in slices up to 30 km altitude. The lidar exploits the Doppler shifts from the reflecting aerosols and molecules transported by the wind. In addition, information can be extracted on cloud cover and aerosol content. UV radiation is heavily attenuated by cloud, so a complete wind profile can be derived only in a clear or partly cloud-free atmosphere through cloud gaps. In



This entry reflects the Phase-A configuration





an overcast sky, wind profiles can be derived for the layers above the clouds.

Satellite configuration (Phase-A): conventional box-shaped bus with four side walls attached to central thrust cone by flat shear walls. Electronics mounted on ±X walls (acting as radiators) that also carry the solar wings. Lidar mounted on cone by three bipods.

Attitude/orbit control: the dawn-dusk orbit means that the +Y axis always faces away from the Sun, and the solar wings can be fixed ±X aft/forward along the line of flight. Attitude control to 0.52 mrad by four 10 Nms reaction wheels & three 100 Am^2 magnetorquers. Attitude information from two star trackers, gyros, GPS receiver & two 3-axis magnetometers. Four 1 N blowdown thrusters for orbit adjust; 60 kg hydrazine in central sphere.

Thermal: instrument dissipation of 300 W via 3 L-shaped heat pipes to +Y face to deep space. 215 W from electronics boxes mounted on ±X walls.

Power system: two 3-panel wings (total 8.4 m^2) of Si-BSFR cells providing 920 W EOL (560 W required), supported by 18 Ah NiCd battery. System design driven by laser pulse power.

Communications: raw data downlinked at 3.5 Mbit/s on 5.6 W SSPA L-band to at least two ground stations. 2 kbit/s TC & 64 kbit/s TM S-band. Antennas mounted on lidar baffle. ADM controlled from ESOC via Kiruna. ESA will process & calibrate the data before sending it to a dedicated science data centre, which will be responsible for quality control and dissemination within 3 h of observation to meteorological centres and other users.

ADM-Aeolus Payload

ALADIN

The Atmospheric Laser Doppler Instrument (ALADIN) uses a 1 m^2 main Cassegrain mirror, surrounded by a 1.2 m-dia baffle. Diode-pumped Nd:YAG laser generates 130 mJ (150 mJ goal) 100 Hz pulses for 7 s (+1 s warm-up). ALADIN aims 35° off-nadir and at 90° to the flight direction to avoid Doppler shift from ADM's own velocity. A measurement is made every 200 km over a length of 50 km (integrated from 3.5 km steps; 1 km steps possible) in 7 s. A wind accuracy of 2-3 m/s is required, for vertical steps selectable 0.5-2 km. Raw data are downlinked for ground processing.

BepiColombo

Planned achievements: first dual Mercury orbiters; first Mercury lander; third mission to Mercury; first European deep-space probe using electric propulsion
Launch date: planned August 2009 (arriving October 2012)
Mission end: nominally after 1 year in orbit around Mercury (lander 1 week)
Launch vehicle/site: two Soyuz-Fregats from Baikonur Cosmodrome, Kazakhstan
Launch mass: about 1500 kg (1100 kg delivered to Mercury)
Orbit: heliocentric transfer to 400x11800 km (MMO) and 1500 km (MPO) polar Mercury orbits
Principal contractors: definition study Alenia Spazio (I) & Astrium GmbH (D)

As the nearest planet to the Sun, Mercury has an important role in learning how planets form. Mercury, Venus, Earth and Mars make up the family of terrestrial planets, each carrying information that is essential for tracing the history of the whole group. Knowledge about their origin and evolution is a key to understanding how conditions supporting life arose in the Solar System, and possibly elsewhere. As long as Earth-like planets orbiting other stars remain inaccessible to astronomers, the Solar System is the only laboratory where we can test models applicable to other planetary systems. The exploration of Mercury is therefore of fundamental importance for answering questions of astrophysical and philosophical significance, such as 'Are Earth-like planets common in the Galaxy?'

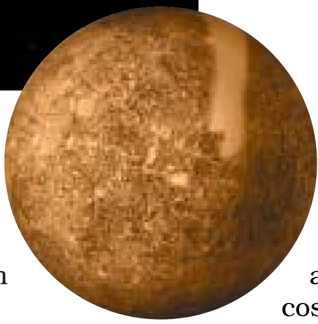
A Mercury mission was proposed in May 1993 for the M3 selection (eventually won by Planck). Although the assessment study showed it to be too costly for a medium-class mission, it was viewed so positively by ESA that, when the Horizon 2000 science programme was extended in 1994 with Horizon 2000 Plus, the three new Cornerstones included a Mercury orbiter. GAIA competed in 2000 with BepiColombo for the fifth Cornerstone slot. In October 2000, the Science Programme Committee approved a package of missions for 2008-2013: BepiColombo was selected as CS-5 (2009) and GAIA as CS-6 (2012). The SPC in September 1999 named the mission in honour of Giuseppe (Bepi) Colombo (1920-1984). The Italian scientist explained Mercury's peculiar rotation - it turns three times for every two circuits around the Sun – and suggested to NASA that an appropriate orbit for Mariner-10 would allow several flybys in 1974-75.

That US probe remains the only visitor to Mercury, so there are many questions to be answered, including:

– what will be found on the unseen hemisphere?
– how did the planet evolve geologically?
– why is Mercury's density so high?
– what is its internal structure and is there a liquid outer core?
– what is the origin of Mercury's magnetic field?
– what is the chemical composition of the surface?
– is there any water ice in the polar regions?
– which volatile materials form the vestigial atmosphere (exosphere)?

The pre-definition study design for BepiColombo. In the foreground is MPO, with the Solar Electric Propulsion Module still attached via the conical interface that houses the Chemical Propulsion Module. In the background is the MMO/MSE composite.

The mission configuration described here reflects the October 2000 baseline. Alternative concepts, such as a single spacecraft-composite launch on an Ariane-5, are possible.



– how does the planet's magnetic field interact with the solar wind?

BepiColombo's other objectives go beyond the exploration of the planet and its environment, to take advantage of Mercury's proximity to the Sun:

– fundamental science: is Einstein's theory of gravity correct?
– impact threat: what asteroids lurk on the sunward side of the Earth?

A 1-year System and Technology Study completed in April 1999 revealed that the best way to fulfil the scientific goals is to fly two Orbiters and a Lander:

– the Mercury Planetary Orbiter (MPO), a 3-axis stabilised and nadir-pointing module in a low orbit for planet-wide remote sensing, radio science and asteroid observations;
– the Mercury Magnetospheric Orbiter (MMO), a spinner in an eccentric orbit, accommodating mostly the field, wave and particle instruments;
– the Mercury Surface Element (MSE) lander, for in situ physical, optical, chemical and mineralogical observations that also provide ground-truth for the remote-sensing measurements.

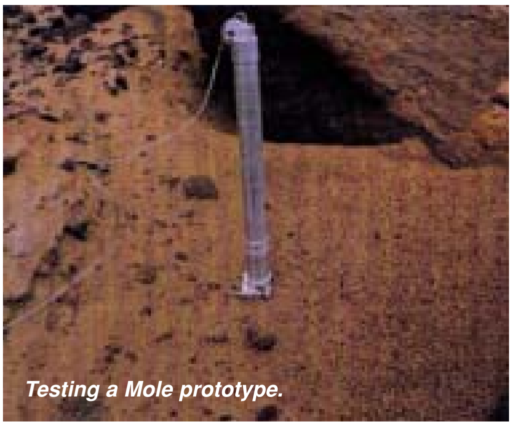
How to deliver these elements to their destinations emerged from a trade-off between mission cost and launch flexibility. It combines electrical propulsion, chemical propulsion and planetary gravity assists. Interplanetary transfer is performed by a Solar Electric Propulsion Module (SEPM), jettisoned upon arrival. The orbit injection manoeuvres then use a Chemical Propulsion Module (CPM), which is also jettisoned once the deployment of the spacecraft elements, MSE included, is completed.

A two-launch scenario, with the spacecraft elements divided into two composites using near-identical propulsion elements, is considered as the baseline: the MPO and MMO-MSE composites are launched by two Soyuz-Fregats to reach Mercury in 3.5 years. The spacecraft concept is modular, however, and lends itself to a variety of schemes compatible with the mission objectives.

Two competing industrial definition studies are being conducted from May 2001 to late 2002 to prepare for the 1-year Phase-B to begin by mid-2003 and Phase-C/D in 2004. Japan's ISAS space agency will provide the MMO element. An Announcement of Opportunity for the MPO/MSE scientific payloads will be made by mid-2002. ISAS' own AO for MMO may be slightly later.

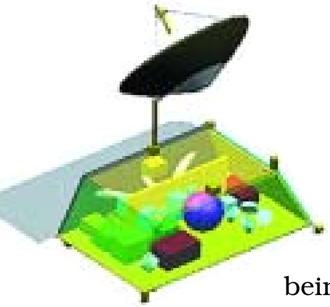
BepiColombo Scientific Instruments

Instrument		*Measurements*	*Mass (kg)*	*Power (W)*
MPO				
Narrow-angle camera Wide-angle camera	NAC WAC	imaging, 350-1050 nm, resolution up to 10 m imaging, 350-1050 nm, 200 m-resolution global map	12	16
IR spectrometer	IRS	mineralogical mapping, up to 150 m/pixel, 0.8-2.8 µm, 128 channels	6	10
UV spectrometer	ALI	UV photometry, 70-330 nm, Al, S, Na & OH in exosphere	3.5	3
X-ray spectrometer	MXS	0.5-10 keV, surface mineral composition	4.5	8
Gamma-ray spectrometer	MGS	0.1-8 MeV, surface elemental composition	7.5	5
Neutron spectrometer	MNS	0.01-5 MeV, surface elemental composition	5	3
Radioscience - Transponder - Accelerometer	RAD KAT ISA	core & mantle structure, Mercury orbit, fundamental science 32-34 GHz 10^{-4}-10 Hz	 3.5 8	 9 6.3
Laser altimeter	TOP	1064±5 nm, topographic mapping	6.5	10
Telescope	NET	+18 mag, 2° FOV, 880 mm fl search for Near-Earth Objects	8	15
MMO				
Magnetometer	MAG	±4096 nT, two tri-axial fluxgate sensors on radial boom	0.88	0.35
Ion mass spectrometer	IMS	50 eV–35 keV, mass, charge & energy of ion species	4.4	4
Electron electrostatic analyser	EEA	0-30 keV, 3-D distribution of plasma electrons	1.1	1.2
Cold plasma analyser	CPA	0-50 eV, energy & composition of low-energy ions	1.3	1.9
Energetic plasma detector	EPD	30-300 keV, energy & composition of high-energy ions	1.2	0.7
Search coil Electric antenna	RPW-H RPW-E	0.1 Hz - 1 MHz, tri-axial magnetometer on boom 0.1 Hz - 16 MHz, two 35 m radial wires	5.1	4
Positive ion emitter	PIE	1-100 µA, indium ions emitted to control craft's potential	2.7	3.8
Camera	SCAM	surface imaging, 350-1000 nm, 10-20 m/pixel	8	12
MSE				
Heat flow and physical properties package (Mole)	HP3	thermistor string, accelerometer, radiation densitometer for temperature, thermal conductivity, density, hardness	1	0.3
Alpha X-ray spectrometer (Microrover)	AXS	elemental composition using Cm-244 X-ray fluorescence (Na, Mg, Al, Si, K, Ca, Fe, P, S, Cl, Ti, Mn, Ni) & α-backscatter (C, O)	0.8	1
Descent camera (on CPM)	CLAM-D	descent images down to 100 m altitude; 4-position filter wheel	0.5	3
Surface camera	CLAM-S	panoramic camera to characterise landing site	0.2	3
Magnetometer	MLMAG	surface magnetic properties	0.5	0.6
Seismometer	SEISMO	crust/mantle 'quakes, tidal deformations	0.9	0.6
Mole	MDD	penetrate several m of regolith with HP3	0.4	5
Microrover	MMR	deploy AXS to several sites; 100 m tether	2	3



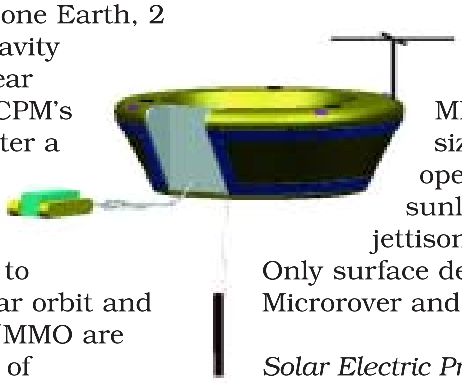
Testing a Mole prototype.

Microrover will measure rock composition.



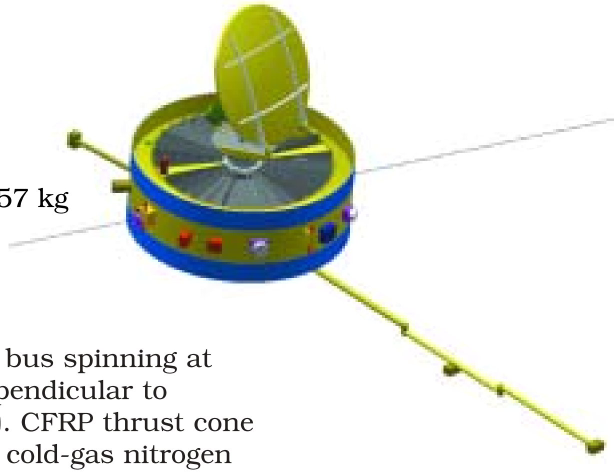
Key technologies are being developed 2001-2004: high-temperature thermal control (materials, louvres, heat pipes embedded in structural panels); high-temperature solar arrays (GaAs cells, arrays, drive mechanisms); high-temperature high-gain antennas (reflector materials, feed and pointing/despin mechanisms); miniaturised integrated avionics; vision-based navigation for landing; robotics and science instruments for surface operations. SMART-1 will demonstrate the use of an electric thruster for primary propulsion.

Mission profile: each composite is launched into Earth orbit with a high apogee (312 500 km), leading to a lunar swingby to set up one Earth, 2 Venus and 2 Mercury gravity assists during the 3.5-year cruise. At Mercury, the CPM's 4 kN engine burns to enter a 400x11800 km polar orbit. MSE/CPM are released here to land. For MPO, CPM reignites to set up a 1500 km circular orbit and is then jettisoned. MPO/MMO are both designed for 1 year of observations (4 Mercury years).



Once MMO is released, CPM burns to reach 10 km perigee in 75 min. It reignites to kill the descent speed at 120 m altitude, where MSE separates and freefalls to the surface for the 30 m/s to be cushioned by airbags. Thermal considerations require a landing site around 85°N/S. During the planned 1 week of surface operations, MSE transmits its data to MPO or MMO.

MPO: configuration driven by thermal constraints, requiring high-efficiency insulation and 1.5 m^2 (200 W rejection) radiator. Bus is a flat prism with 3 sides slanting 20° as solar arrays, providing 420 W at perihelion (30% cells, 70% optical solar reflectors). 1.5 m dia Ka-band HGA delivers 1550 Gbit in 1 year. UHF antenna for MSE surface link. 3-axis control, nadir-pointing. Mass 357 kg (including 60 kg science payload).



MMO: cylindrical bus spinning at 15 rpm (axis perpendicular to Mercury equator). CFRP thrust cone houses tanks for cold-gas nitrogen thrusters. Hardware mounted on walls and 2 platforms; top/bottom faces are radiators. Despun X-band 20 W HGA delivers 160 Gbit in 1 year; 2 MGAs. UHF patch antenna for MSE surface link. Mass 165 kg (including 24 kg science payload).

MSE: truncated cone 90 cm dia, 44 kg (including 7 kg science payload) delivered to surface by CPM + airbags. 8.7 kbit/s to MMO or MPO, 1.7 kWh battery sized for 1-week operations. If lands in sunlight, top cover jettisoned to expose radiator. Only surface deployables are tethered Microrover and Mole.

Solar Electric Propulsion Module: identical for both composites, provides cruise propulsion (jettisoned before Mercury insertion). Three 200 mN Xe ion thrusters powered by 2 wings totalling 33 m^2 of GaAs cells delivering 5.5 kW at 1 AU. Wings tilt to maintain T < 150°C. Box-shaped bus, with central thrust cone (housing Xe tanks) as launcher interface. Mass 600 kg (366 kg dry).

Chemical Propulsion Module: provides Mercury capture and orbit manoeuvres. Acts as structural interface between SEPM and science craft (interface cone caps SEPM's thrust cone and mounts to MMO/MPO), and houses CLAM-D camera for MSE descent imaging. 4 kN bipropellant engine with redundant 8x20 N attitude thrusters. Propellant load 156/334 kg MPO/MMO-MSE in 4 spheres; dry mass 71 kg.

Top left: MPO cutaway. Top right: MMO in operational configuration. Left: MSE deployed on the surface, with the tethered Microrover and the burrowing Mole.

NGST

Planned achievements: observe the Universe back to the time of the first stars; extend the NASA/ESA Hubble Space Telescope collaboration
Launch date: about 2009
Mission end: after 5 years (consumables sized for 10 years)
Launch vehicle/site: to be decided (Atlas/EELV/Ariane-5 class)
Launch mass: < 3700 kg
Orbit: planned halo orbit around L2 Lagrangian point, 1.5 million km from Earth
Principal contractors: to be selected. 12-month ESA Phase-A planned start mid-2001, 18-month Phase-B 2002, 33-month Phase-C/D 2004, for ESA hardware delivery to NASA in 2006

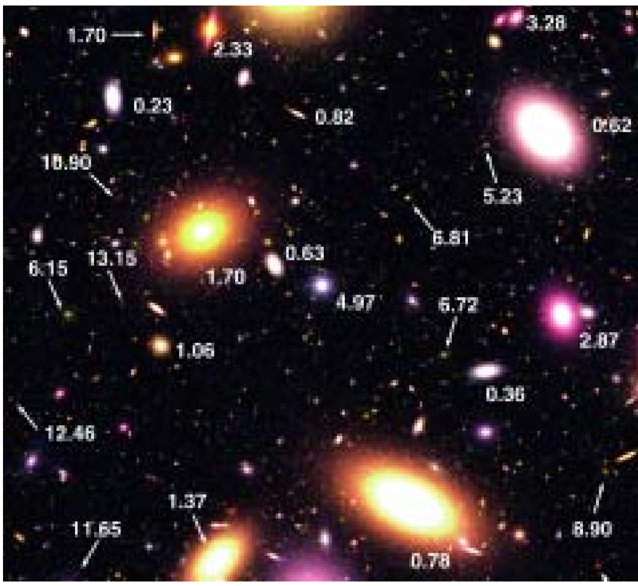
The NASA/ESA Hubble Space Telescope (HST) is one of the most successful astronomical space projects ever undertaken. The equal access to the observatory gained through ESA's active participation in the mission from the very beginning is hugely beneficial scientifically to the European astronomical community.

Since 1996, NASA, ESA and the Canadian Space Agency (CSA) have been collaborating on defining a worthy successor to HST – the Next Generation Space Telescope (NGST). By participating at the financial level of a Flexi-mission, ESA will gain a partnership of about 15% in the observatory as well as continued access to HST (qv). In October 2000, ESA's Science Programme Committee approved a package of missions for 2008-2013, including NGST as the F2 Flexi mission.

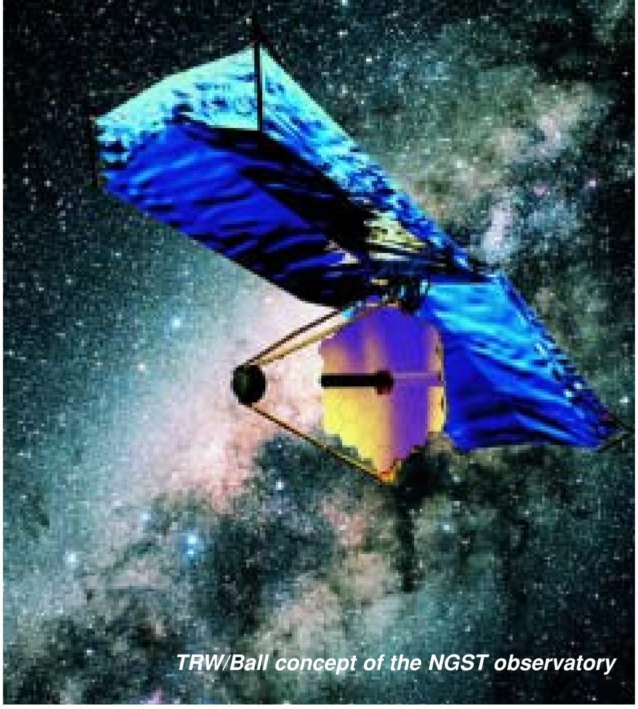
NGST is seen as a 6 m-class telescope, optimised for the near-IR (1-5 µm) region, but with extensions into the visible (0.6-1 µm) and mid-IR (5-28 µm). The large aperture and shift to the infrared is driven by the desire of astronomers to probe the Universe back in time and redshift to the epoch of 'First Light', when the very first stars began to shine, perhaps less than 1000 million years after the Big Bang. Nonetheless, like HST, NGST will be a general-purpose observatory, with a set of instruments to address a broad spectrum of outstanding problems in galactic and extragalactic astronomy. In contrast with its predecessor, NGST will be placed in a halo orbit around the L2 Lagrangian point, so will not be accessible for servicing after launch.

The Design Reference Mission covers the first 2.5 years of observations, with 23 programmes touching almost all areas of modern astrophysics:

- cosmology and structure of the Universe,
- origin and evolution of galaxies,
- history of the Milky Way and its neighbours,
- the birth and evolution of stars,



Simulated NGST image with redshifts marked. NGST could detect some 100 galaxies with redshifts >5 in this small fraction (< 1%) of the camera field of view. (Myungshin Im, Space Telescope Science Institute)



TRW/Ball concept of the NGST observatory

– origins and evolution of planetary systems.

NASA has two competing prime contractor teams (TRW and Lockheed Martin), one of which will win the contract to build the observatory following the Request for Proposals in 2001. Detailed assessment studies of a wide range of instrument concepts for NGST have been funded by the three agencies and carried out by their scientific communities and industries. Based on these studies, the recommended suite consists of three core instruments:

– a near-IR Wide-Field Camera covering 0.6-5 μm;
– a near-IR Multi-Object Spectrograph covering 1-5 μm;
– a mid-IR combined Camera/Spectrograph covering 5-28 μm.

Guided by this recommendation, the three agencies agreed in July 2000 on their contributions. ESA's will closely follow the HST model, with three main elements:

Scientific instrumentation: ESA will procure about half of the core payload, principally providing the near-IR Multi-Object Spectrograph. In addition, through special contributions from its Member States, ESA will provide 50% of the mid-IR Camera/Spectrograph (optics, structure and mechanisms), to be developed jointly by NASA/ESA/CSA.

NGST Science Goals

1. *Formation and evolution of galaxies (imaging).*
2. *Formation and evolution of galaxies (spectra).*
3. *Mapping dark matter*
4. *Searching for the reionisation epoch.*
5. *Measuring cosmological parameters.*
6. *Formation and evolution of galaxies – obscured stars and Active Galactic Nuclei.*
7. *Physics of star formation: protostars.*
8. *Age of the oldest stars.*
9. *Detection of jovian planets.*
10. *Evolution of circumstellar discs.*
11. *Measure supernovae rates.*
12. *Origins of substellar-mass objects.*
13. *Formation and evolution of galaxies: clusters.*
14. *Formation and evolution of galaxies near AGN.*
15. *Cool-field brown dwarf neighbours.*
16. *Survey of trans-neptunian objects.*
17. *Properties of Kuiper Belt Objects.*
18. *Evolution of organic matter in the interstellar medium – astrobiology.*
19. *Microlensing in the Virgo cluster.*
20. *Ages and chemistry of halo populations.*
21. *Cosmic recycling in the interstellar medium.*
22. *IR transients from gamma-ray bursts and hosts.*
23. *Initial Mass Function of old stellar populations.*

Non-instrument flight hardware: ESA will provide the Service Module (assumed to be derived from the Herschel bus) or, if that proves impractical, SM subsystems plus some amount of optical figuring and polishing of the telescope mirrors.

Contributions to operations: ESA will participate in operations at a similar level to HST.

Through these contributions, ESA will secure for astronomers from its Member States full access to the NGST observatory on identical terms to those enjoyed today on HST – representation on all project advisory bodies, and observing time allocated via a joint peer review process, backed by a guaranteed 15% minimum.

The telescope and instruments will be passively cooled in bulk behind a large deployable sunshade to below 50 K, a level determined by the operating temperature of the InSb and HgCdTe 1-5 μm detector arrays. The Si:As detectors to reach beyond 5 μm require the mid-IR instrument to be cooled to ~8 K by a cryostat. The 0.6 μm lower wavelength limit allows a gold coating to be used as the reflecting surface in the telescope and instrument optics.

Science configuration: 3-mirror anastigmat telescope, 6 m-diameter primary (folded for launch), f/24 or f/16, diffraction-limited at 2 μm. Image stability 10 mas using fast-steering mirror controlled by a fine guidance sensor in the focal plane. Instrument module 2.5x2.5x3.0 m, < 1000 kg.

Bus: Pointing accuracy 2 arcsec rms. < 1000 W required from solar array. 1.6 Mbit/s from science instruments, stored on 100 Gbit SSR, downlinked at X-band.

LISA

Planned achievements: first detection of gravitational waves, first direct measurements of massive black holes at centres of galaxies
Launch date: planned for August 2011 (science phase begins 2012)
Mission end: nominally after 2 years (8-year extension possible)
Launch vehicle/site: Delta-II from Complex 17, Cape Canaveral, Florida
Launch mass: total 1380 kg (on-station 274 kg each, science payload 70 kg each)
Orbit: heliocentric, trailing Earth by 20°
Principal contractors: to be selected; System & Technology Study June 1999 - February 2000; LISA Technology Demonstration in Space (part of SMART-2) October 2006 - January 2007; Phase-B June 2006 - October 2007, Phase-C/D November 2007 - May 2011

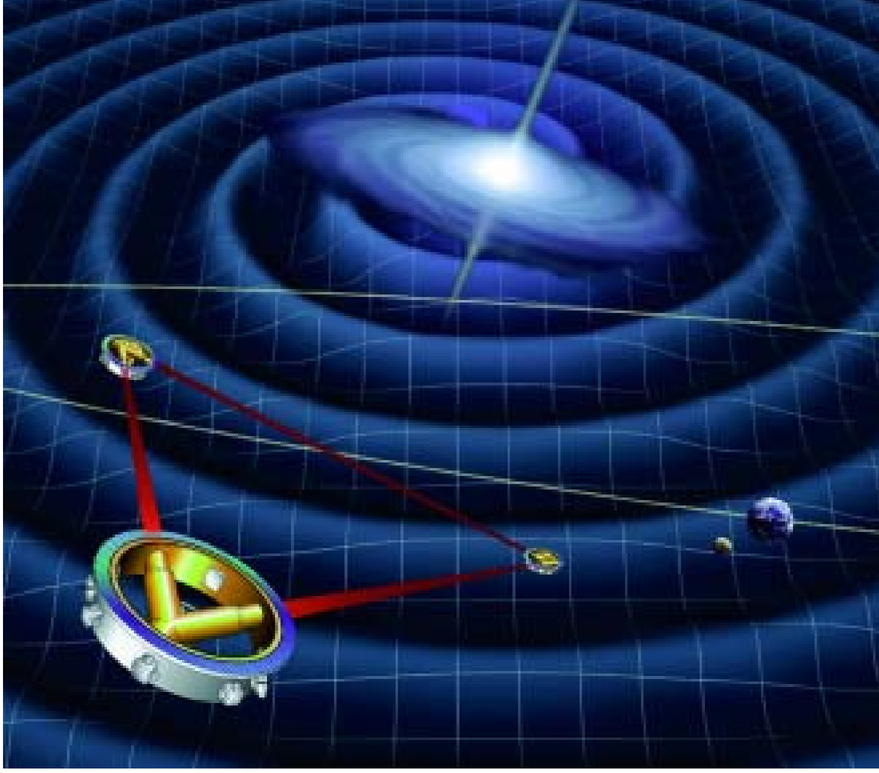
ESA's ambitious Laser Interferometer Space Antenna (LISA) aims to make the first detection of gravitational waves – ripples in space-time. According to Einstein's Theory of General Relativity, these waves are generated by exotic objects such as binary black holes, which distort space and time as they orbit closely. To detect the elusive gravitational waves, the three LISA satellites will carry state-of-the-art inertial sensors, a laser-interferometry telescope system and highly sensitive ion thrusters.

In October 2000, the Science Programme Committee approved a package of missions for 2008-2013. LISA will fly as Cornerstone 7 (Fundamental Physics), but in collaboration with NASA at a cost to ESA of a Flexi mission. The demanding technologies will be tested by the dedicated SMART-2 demonstrator in 2006, during LISA's Phase-B.

A 4-spacecraft version of LISA was proposed to ESA in May 1993 for the M3 competition (won by Planck), but that version clearly exceeded the cost limit for a medium-class mission. A 6-spacecraft version was proposed in December 1993 as a Cornerstone for the Horizon 2000 Plus programme, and selected. Being a Cornerstone implies the mission is approved, but the launch date depends on funding levels. The 6-spacecraft version was earmarked for launch after 2017. By early 1997, the cost had been drastically reduced by halving the number of satellites and through collaboration with NASA.

Massive bodies produce indentations in the elastic fabric of spacetime, like billiard balls on a springy surface. If a mass distribution moves aspherically, then the spacetime ripples spread outwards as gravitational waves. A perfectly symmetrical collapse of a supernova will produce no waves, while a non-spherical one will emit gravitational radiation. A binary system always radiates.

As gravitational waves distort spacetime, they change the distances between free bodies. Gravitational waves passing through the Solar System changes the distances between all bodies in it. This could be the distance between a spacecraft and Earth, as in the cases of Ulysses and Cassini (attempts continue to measure these distance fluctuations), or the distances between shielded proof masses inside well-spaced satellites, as in LISA. The main problem is that the distance changes are exceedingly small. For example, the periodic change between two proof masses owing to a typical white dwarf binary at a distance of 50 pc is only 10^{-10} m.



LISA will fly a troika of identical satellites in an equilateral triangle formation to detect distance changes as they surf gravitational waves passing through the Solar System.

Gravitational waves are not weak (a supernova in a not too-distant galaxy drenches every square metre on Earth with kilowatts of gravitational radiation), but the resulting length changes are small because spacetime is such an extremely stiff elastic medium that it takes huge energies to produce even minute distortions.

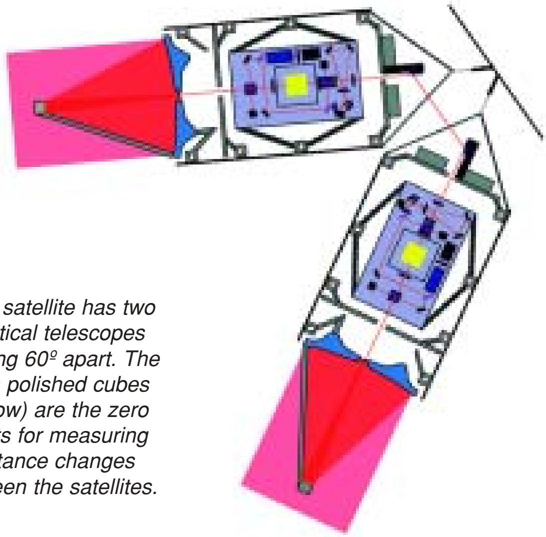
If LISA does not detect the gravitational waves from known binaries with the intensity and frequency predicted by Einstein's General Relativity, it will shake the very foundations of gravitational physics.

LISA's main objective is to learn about the formation, growth, space density and surroundings of massive black holes (MBHs). There is now compelling indirect evidence for the existence of MBHs with masses of 10^6 - 10^8 Suns in the centres of most galaxies, including our own. The most powerful sources are the mergers of MBHs in distant galaxies. Observations of these waves would test General Relativity and, particularly, black-hole theory to unprecedented accuracy. Not much is known about black holes of masses from 100 to 10^6 Suns. LISA can provide unique new information throughout this mass range.

LISA uses identical satellites 5 million km apart in an equilateral triangle. It is a giant Michelson interferometer, with a third arm added for redundancy and independent information on the waves' two polarisations. Their separations (the interferometer arm length) determine LISA's wave frequency range (10^{-4} - 10^{-1} Hz), carefully chosen to cover the most interesting sources of gravitational radiation.

The centre of the triangular formation is in the ecliptic plane 1 AU from the

LISA satellite configuration. The Y-shaped twin-telescope assembly is supported by a carbon-epoxy ring. The top solar array is not shown, nor the bottom propulsion module.



Each satellite has two identical telescopes pointing 60º apart. The 4 cm polished cubes (yellow) are the zero points for measuring distance changes between the satellites.

Sun and 20° behind the Earth. The plane of the triangle is inclined 60° to the ecliptic. This configuration means that the formation is maintained throughout the year, and appears to rotate around its centre annually.

Each satellite contains two optical assemblies, each pointing to an identical assembly on each of the other satellites. A 1 W 1.064 µm IR Nd:YAG laser beam is transmitted via a 30 cm-aperture f/1 Cassegrain telescope. The other satellite's own laser is phase-locked to the incoming light, providing a return beam with full intensity. The first telescope focuses the very weak beam (a few pW) from the distant spacecraft and directs it to a sensitive photodetector, where it is superimposed with a fraction of the original local light, serving as a local oscillator in a heterodyne detection. The distance fluctuations are measured to sub-Å precision which, combined with the 5 million km separations, allows LISA to detect gravitational-wave strains down to one part in 10^{-23} in a year of observation with a signal-to-noise ratio of 5.

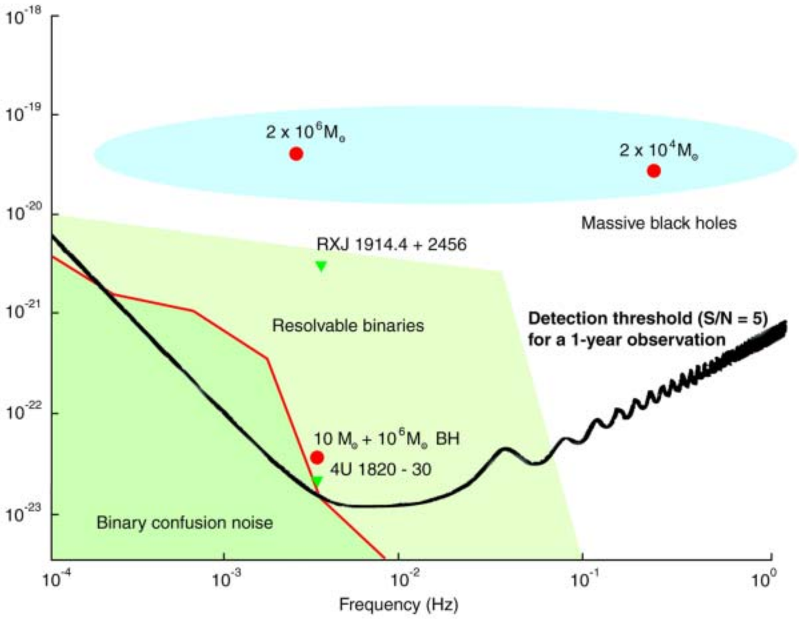
At the heart of each assembly is a vacuum enclosure housing a free-flying polished platinum-gold 4 cm cubic proof mass, which serves as the optical reference mirror for the lasers. The spacecraft serve mainly to shield the proof masses from solar radiation pressure, and the spacecraft's actual position does not directly enter into the measurement. It is nevertheless necessary to keep them moderately centred (10^{-8} m/√Hz in the measurement band) on their proof masses to reduce spurious local noise forces. This is done by a drag-free control system consisting of an accelerometer (or inertial sensor) and a system of µN thrusters. 3-D capacitive sensing measures the displacements of the proof masses relative to the spacecraft. These position signals are used to command Field-Emission Electric Propulsion (FEEP) thrusters to enable the spacecraft to follow its proof masses precisely. The thrusters also control the attitude of the spacecraft relative to the incoming optical wave fronts using signals derived from quadrant

SMART-2

Planned achievements: technology demonstrator for LISA and Darwin
Launch date: planned for August 2006
Launch vehicle/site: Soyuz-Fregat from Baikonur Cosmodrome, Kazakhstan
Orbit: heliocentric, trailing Earth by 20°
Principal contractors: to be selected

LISA relies on technology validated by the SMART-2 precursor mission, approved by the SPC in February 2001. Fifteen Technology Development Activities are proving that LISA's extreme sensitivity values can be achieved. These activities will be completed in 2002 and consolidated into the LISA Test Package (LTP) for flight on SMART-2. The prime contractor will be selected and Phase-B started by November 2002. The flight will provide feedback to the then-running LISA Phase-B. LTP covers LISA's proof-mass sensor, FEEP thruster package and the control law software. The main satellite will carry one or two LTPs (depending on NASA participation). Using a second satellite, SMART-2 will also demonstrate the formation flying and inter-satellite metrology required for IRSI-Darwin.

LISA's sensitivity to binary stars in our Galaxy and black holes in distant galaxies. The heavy black curve shows LISA's detection threshold after a year's observations. The vertical scale is the distance change detected (one part in 10^{23} is the goal). At frequencies below 10^{-3} Hz, binary stars in the Galaxy are so numerous that LISA will not resolve them (marked 'Binary confusion noise'). In lighter green is the region where LISA should resolve thousands of binaries closer to the Sun or radiating at higher frequencies. The signals expected from two known binaries are indicated by the green triangles. The blue area covers waves expected from massive black holes merging in other in galaxies (redshift z = 1). The red spots mark the mergings of two million-solar-mass black holes, and two 10 000-solar-mass black holes. The bottom red spot shows the expected wave from a 10-solar-mass black hole falling into one of a million solar masses, at a distance of z = 1.



photodiodes. As the constellation orbits the Sun in the course of a year, the observed gravitational waves are Doppler-shifted by the orbital motion. For periodic waves with sufficient signal-to-noise ratio, this allows the direction of the source to be determined to arcminute or degree precision, depending on source strength.

LISA is envisaged as a NASA/ESA collaboration: NASA provides launch, X-band communications, mission and science operations, and about 50% of the payload; ESA provides the three spacecraft, including the ion drives; European institutes, funded nationally, provide the other 50% of the payload.

Satellite configuration: total diameter 2.2 m across solar array. Main structure is a 1.80 m-dia, 48 cm-height ring of graphite-epoxy (low thermal expansion). Each satellite houses two identical telescopes and optical benches in a Y-shaped configuration.

Attitude control: drag-free/attitude control maintained by 6 clusters of four FEEP thrusters, controlled by feedback loop using capacitive position sensing of proof masses. Performance: 3×10^{-15} m/s^2 in the band 10^{-4} - 10^{-3} Hz. Solar-electric propulsion module (142 kg, 1.80 m-dia, 40 cm-high, CFRP, redundant 20 mN Xe ion thrusters) jettisoned after 13-month transfer from Earth; 4x4.45 N + 4x0.9 N hydrazine thrusters provide 3-axis control and orbit adjust. Attitude from 4 star trackers, Sun sensors.

Power system: 315 W on-station (72 W science), provided from GaAs cells on circular top face, supported by Li-ion batteries. 940 W required during ion-powered cruise, from similar propulsion module array.

Communications: 30 cm-dia X-band steerable antenna transmits science and engineering data (stored onboard for 2 days) at 7 kbit/s to the 34 m network of NASA's Deep Space Network DSN. Total science rate 672 bit/s.

GAIA

Planned achievements: map 1000 million stars at 10 microarcsec accuracy to discover how and when our Galaxy formed, how it evolved and its current distribution of dark matter; fundamental importance for all branches of astronomy; maintain Europe's lead in astrometry
Launch date: planned for 2012
Mission end: 5-year mission planned (4-year observation period); 1-year extension possible
Launch vehicle/site: shared Ariane-5 from Kourou, French Guiana
Launch mass: 3137 kg (2267 kg if Ariane-5 provides transfer orbit injection)
Orbit: planned Lissajous orbit around L2 point 1.5 million km from Earth
Principal contractors: to be determined. Phase-B to begin 2005; Phase-C/D 2006

GAIA aims to solve one of the most difficult but fundamental challenges in modern astronomy: to determine the composition, creation and evolution of our Galaxy, in the process creating an extraordinarily precise 3-D map of more than 1000 million stars throughout the Galaxy and beyond.

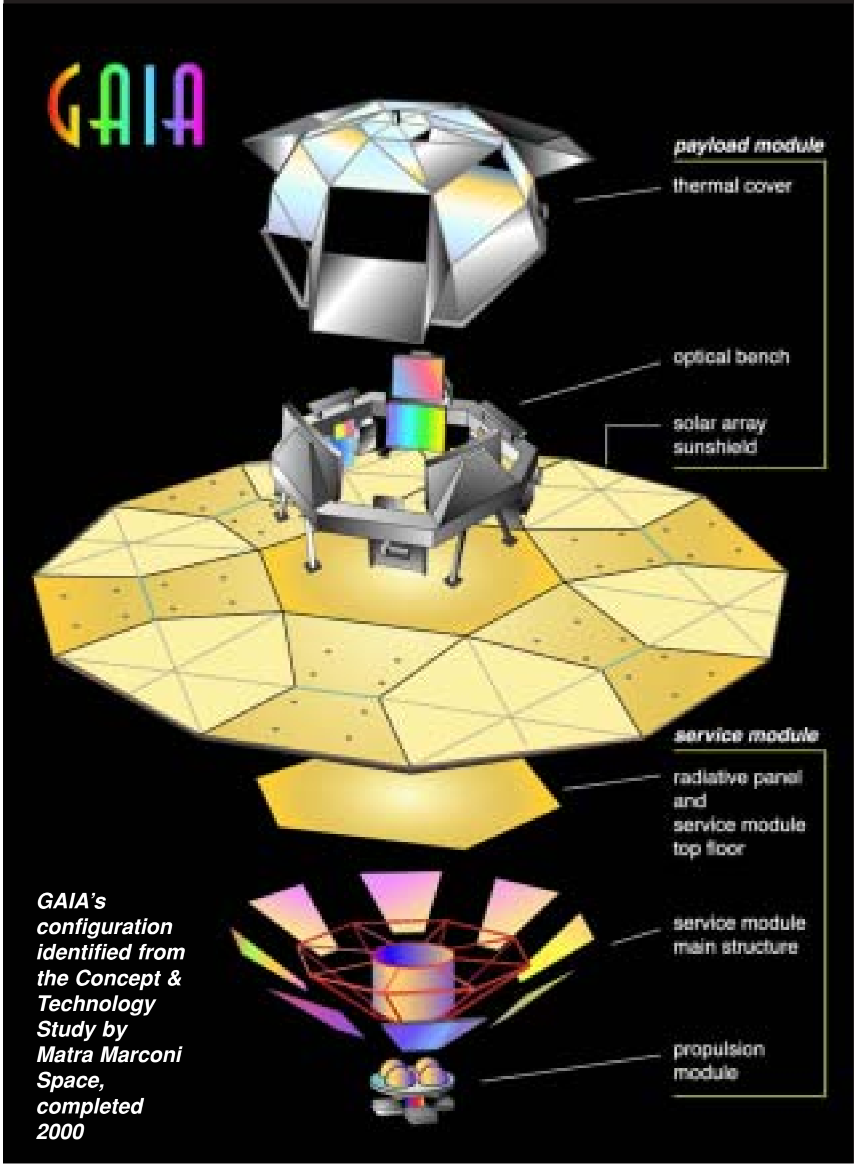
When ESA's Horizon 2000 science programme was extended in 1994 with Horizon 2000 Plus, the three new Cornerstones included an interferometry mission. Two options were proposed. GAIA aimed at 10 microarcsec-level astrometry, while Darwin would look for life on planets discovered around other stars. Following studies, GAIA's interferometric approach was replaced in 1997 by measurements using simpler monolithic mirrors (and GAIA became a name instead of an acronym for Global Astrometric Inteferometer for Astrophysics). GAIA competed in 2000 with BepiColombo for the fifth Cornerstone slot. In October 2000, the Science Programme Committee approved a package of missions for 2008-2013: BepiColombo was selected as CS-5 (2009) and GAIA as CS-6.


(R. Sword)

By combining positions with radial velocities, GAIA will map the stellar motions that encode the origin and evolution of the Galaxy. It will identify the detailed physical properties of each observed star: brightness, temperature, gravity and elemental composition.

GAIA will achieve all this by repeatedly measuring the positions and multi-colour brightnesses of all objects down to magnitude +20. Variable stars, supernovae, transient sources, micro-lensed events and asteroids will be catalogued to this faint limit. Final accuracies of 10 microarcsec (the diameter of a human hair viewed from a distance of 1000 km) at magnitude +15, will provide distances accurate to 10% as far as the Galactic Centre, 30 000 light-years away. Stellar motions will be measured even in the Andromeda Galaxy.

GAIA will provide the raw data to test our theories of how galaxies and stars form and evolve. This is possible because low-mass stars live for much longer than the present age of the Universe, and retain in their atmospheres a fossil record of the chemical elements in the interstellar medium when they formed. Their current orbits are the result of their dynamical histories, so GAIA will identify where they formed and probe the distribution of dark matter. GAIA will establish the luminosity function for pre-main sequence stars, detect and categorise rapid evolutionary stellar phases, place unprecedented constraints on the age, internal structure and evolution of all star types, establish a rigorous distance scale framework throughout the Galaxy and beyond, and classify star formation and movements across the Local Group of galaxies.

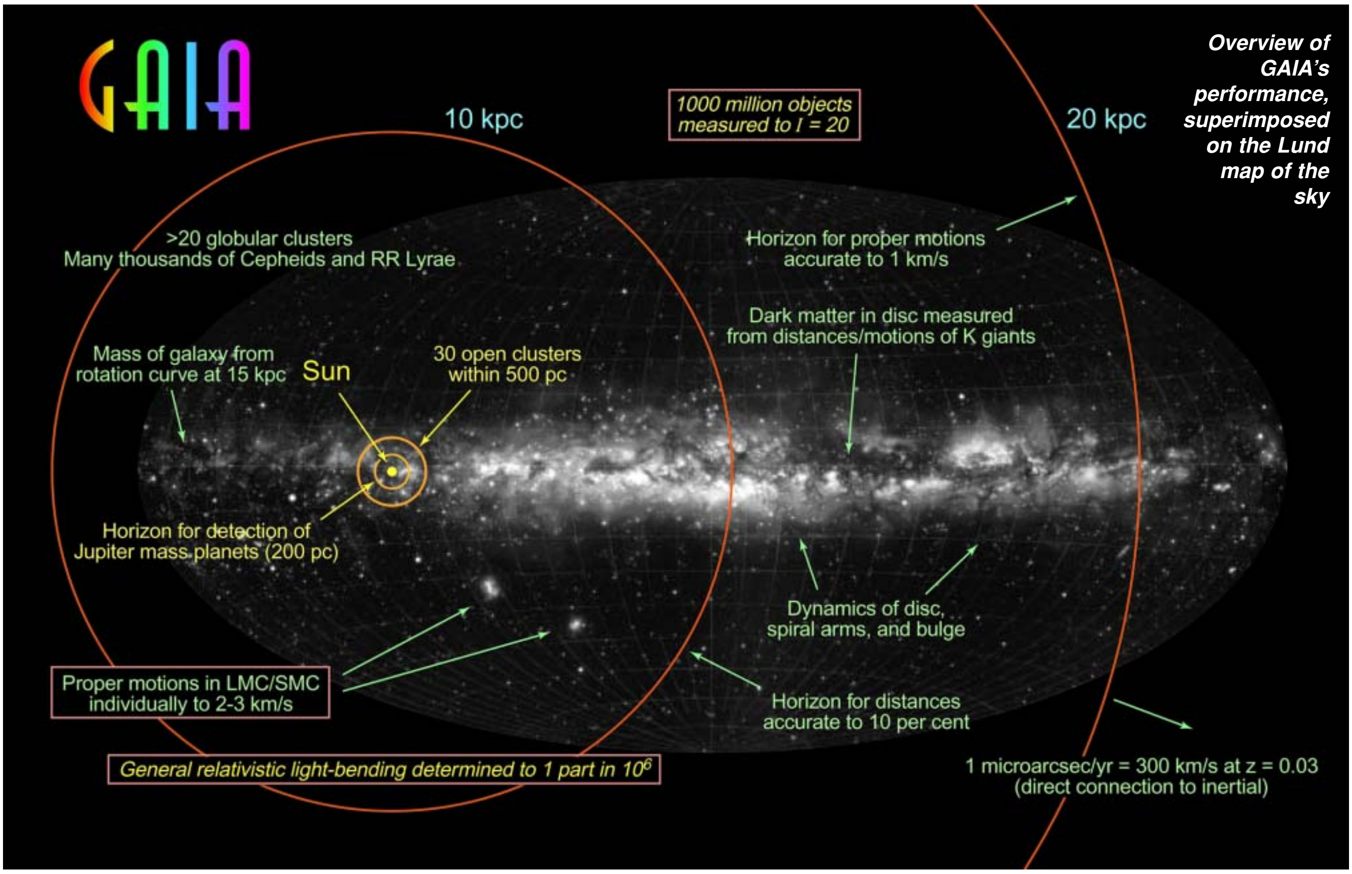


GAIA's configuration identified from the Concept & Technology Study by Matra Marconi Space, completed 2000

GAIA will pinpoint exotic objects in colossal numbers: many thousands of extrasolar planets will be discovered, and their detailed orbits and masses determined; brown dwarfs and white dwarfs will be identified in their tens of thousands; some 100 000 extragalactic supernovae will be discovered in time for ground-based follow-up observations; Solar System studies will receive a massive impetus through the discovery of many tens of thousands of minor planets; inner Trojans and even new trans-Neptunian objects, including Plutinos, will be discovered.

GAIA will also contribute to fundamental physics. It will quantify the bending of starlight by the Sun and major planets over the entire celestial sphere, and therefore directly observe the structure of space-time. GAIA's accuracy will allow the long-sought scalar correction to the tensor form to be determined. The Parameterised Post-Newtonian (PPN) parameters γ and β, and the solar quadrupole moment J_2 will be determined with unprecedented precision. New constraints on the rate of change of the gravitational constant, $\dot{G}$, and on gravitational wave energy over a certain frequency range will be obtained.

Like Hipparcos, GAIA will measure the angles between targets as its rotation scans two telescopes (separated by 106°) around the sky. Processing on the ground will link these targets in a grid with 10 microarcsec accuracy. Distances and proper motions will 'fall out' of the processing, as will information on double and multiple star systems, photometry, variability and planetary systems.



Overview of GAIA's performance, superimposed on the Lund map of the sky

GAIA Measurement Capabilities

Median parallax errors
4 µas at +10 mag
11 µas at +15 mag
160 µas at +20 mag

Distance accuracies
2 million better than 1%
50 million better than 2%
110 million better than 5%
220 million better than 10%

Radial velocity accuracies
1-10 km/s to V = +16-17 mag, depending on spectral type

Catalogue
~1000 million stars
26 million to V = +15 mag
250 million to V = +18 mag
1000 million to V = +20 mag
completeness to about +20 mag

Photometry
to V = +20 mag in 4 broad and 11 medium bands

GAIA Science Goals

Galaxy
origin and history of Galaxy
tests of hierarchical structure formation theories
star-formation history
chemical evolution
inner bulge/bar dynamics
disc/halo interactions
dynamical evolution
nature of the warp
star cluster disruption
dynamics of spiral structure
distribution of dust
distribution of invisible mass
detection of tidally-disrupted debris
Galaxy rotation curve
disc mass profile

Star formation and evolution
in situ luminosity function
dynamics of star-forming regions
luminosity function for pre-main sequence stars
detection/categorisation of rapid evolutionary phases
complete local census to single brown dwarfs
identification/dating of oldest halo white dwarfs
age census
census of binaries/multiple stars

Distance scale and reference frame
parallax calibration of all distance scale indicators
absolute luminosities of Cepheids
distance to the Magellanic Clouds
definition of the local, kinematically non-rotating metric

Local Group and beyond
rotational parallaxes for Local Group galaxies
kinematical separation of stellar populations
galaxy orbits and cosmological history
zero proper motion quasar survey
cosmological acceleration of Solar System
photometry of galaxies
detection of supernovae

Solar System
deep and uniform detection of minor planets
taxonomy and evolution
inner Trojans
Kuiper Belt Objects
disruption of Oort Cloud
near-Earth objects

Extrasolar planetary systems
complete census of large planets to 200-500 pc
orbital characteristics of several thousand systems

Fundamental physics
γ to ~5x10^{-7}
β to 3x10^{-4} - 3x10^{-5}
solar J_2 to 10^{-7} - 10^{-8}
$\dot{G}/G$ to 10^{-12} - 10^{-13} yr^{-1}
constraints on gravitational wave energy for $10^{-12} < f < 4x10^{-9}$ Hz
constraints on Ω_M and Ω_Λ from quasar microlensing

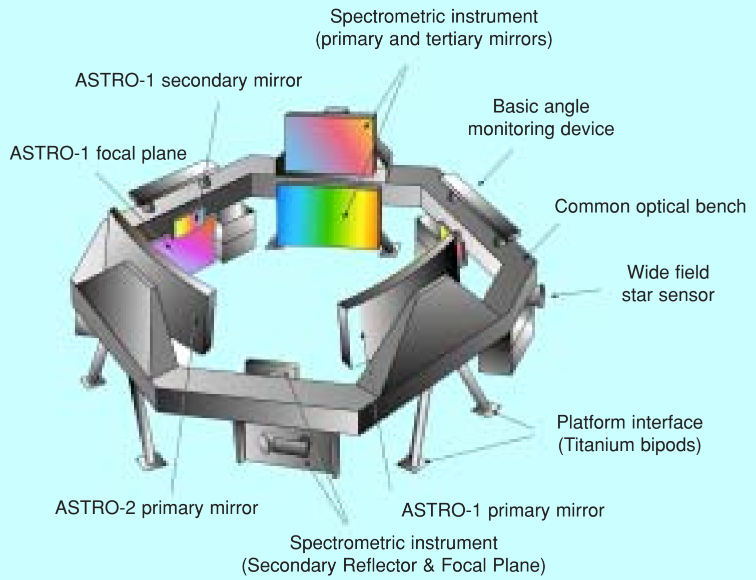
Specific objects
10^6 - 10^7 resolved galaxies
10^5 extragalactic supernovae
500 000 quasars
10^5 - 10^6 (new) Solar System objects
50 000 brown dwarfs
30 000 extrasolar planets
200 000 disc white dwarfs
200 microlensed events
10^7 resolved binaries within 250 pc

The two moderate-size telescopes use large CCD focal plane assemblies, with passive thermal control. GAIA is sized specifically to fit on a shared Ariane-5. A Lissajous orbit around Lagrange point L2 is preferred, from where an average of 1 Mbit/s will return to the single ground station throughout the 5-year mission (totalling 20 Tbytes of raw data). Every one of the 10^9 targets will be observed typically 100 times, each time in a complementary set of photometric filters, and a large fraction also with the radial velocity spectrograph.

Many analyses will be possible even during operations, while some will require the whole mission calibration information or even the final data reduction. GAIA will provide exciting scientific data to a very wide community, beginning with the first photometric observations, and rapidly increasing until the fully reduced data become available 2-3 years after mission-end. The resulting analyses will provide a vast scientific legacy, generating a wealth of quantitative data on which all of astrophysics will build.

Satellite configuration: payload module (PLM) 4.2 m diameter, 2.1 m high; service module (SVM) 4.2/9.5 m diameter (stowed/deployed), PLM/SVM mechanically- and thermally-decoupled, separated by 9.5 m-diameter solar array/sunshield (the only deployable element), SVM interfaces with Ariane-5 standard adapter; structure is aluminium with CFRP shear walls. Lateral panels used as radiators and covered with optical solar reflectors. SVM is at 200°C, PLM at 200K (stability tens of μK). 6 solar wings stowed during launch; insulated from PLM with MLI on rear face. Additional insulation sheets, reinforced with kevlar cables, are spread between the wings.

Attitude/orbit control: 7 caesium-FEEP electric thrusters maintain 120 arcsec/s spin; 3-axis control by



The payload is mounted on a silicon carbide optical bench. Two telescopes separated by 106° are scanned by GAIA's 1 rev/h spin rate, for the simultaneous measurement of the angular separations of thousands of star images as they pass through the 1° FOV. The precise angular separation ('basic angle') of the primary 0.7x1.7 m rectangular mirrors (1° FOV, 50 m f.l.), is continuously measured. Secondary mirrors are adjustable to within 1 μm. Each focal plane has an array of 250 CCDs (each 2150x2780 pixels) forming a 25x58 mm detector. FOV divided into: Astrometric Sky Mapper of 3 CCD strips to identify entering objects; Astrometric Field (0.5x0.66°) for the actual position measurements; 4-band photometer. The third telescope (4° FOV, 4.17 m f.l., entrance pupil 75x70 cm) is a spectrometer, for radial velocity (from Doppler shift) measurements using 3 large CCDs and medium-band photometry using 2 large CCDs with 11 filters.

10 N thrusters during 220-240 day transfer orbit to L2 point, powered by 400 N liquid-propellant thruster (not required if Ariane-5 has restartable engine). Lissajous eclipse-free orbit around L2 provides stable thermal environment, high observing efficiency (Sun, Earth and Moon always out of fields of view) and low-radiation environment.

Power system: 2569 W required, including 1528 W payload, 640 W SVM. Two panels of GaAs cells on each of 6 CFRP solar wings, totalling 24.1 m^2.

Communications: 17 W X-band high-gain, electronically-steered phased-array antenna provides 3 Mbit/s (minimum 1 Mbit/s) to ESA's 35 m-diameter Perth ground station 8 h daily. SSR ≥200 Gbit, sized to hold full day's data. Contolled from ESOC. Low-gain omni antenna for TC and housekeeping TM.

Solar Orbiter

Planned achievements: closest-ever solar approach; highest-resolution solar observations; first images of the Sun's polar regions
Launch date: planned for February-March 2012 (Venus window every 18 months)
Mission end: after 5 years (2-year extension possible)
Launch vehicle/site: Soyuz-Fregat from Baikonur Cosmodrome, Kazakhstan
Launch mass: about 1300 kg (130 kg science payload)
Orbit: planned operational ~0.21x0.9 AU, up to 30°, 149-day heliocentric
Principal contractors: to be selected. Possible schedule: 18-month Phase-A 2006-2008, 12-month Phase-B 2008-2009, 36-month Phase-C/D 2009-2012

On 1 October 1999, ESA requested proposals for the F2 and F3 Flexi science missions, selecting five of the 50 for assessment studies March-May 2000: Eddington, Hyper, MASTER, Solar Orbiter and Storms; the Next Generation Space Telescope was already part of the process. In October 2000, the Science Programme Committee approved a package of missions for implementation in 2008-2013, including Solar Orbiter as a Flexi mission.

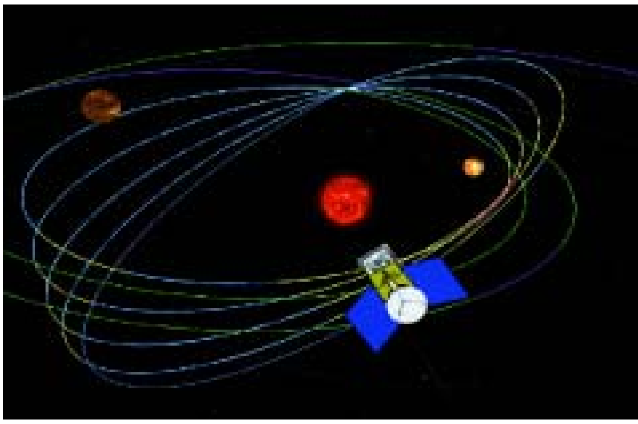
The Sun's atmosphere and the heliosphere are unique regions of space, where fundamental physical processes common to solar, astrophysical and laboratory plasmas can be studied in detail and under conditions impossible to reproduce on Earth. The results from Soho and Ulysses have enormously advanced our understanding of the solar corona, the associated solar wind and the 3-D heliosphere. However, we have reached the point where in situ measurements much closer in to the Sun, combined with high-resolution imaging and spectroscopy at high latitudes, promise to bring about major breakthroughs.

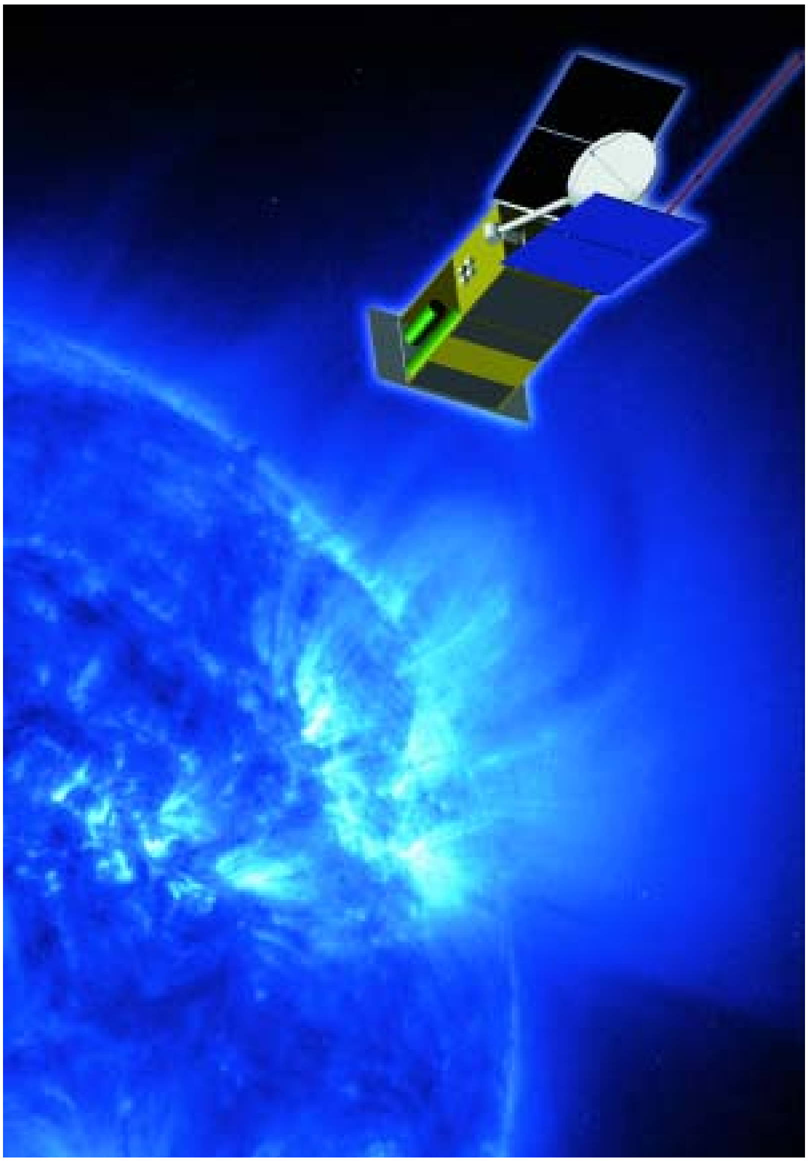
The Solar Orbiter, through a novel orbit design and its state-of-the-art instruments, will provide exactly the observations required. For the first time, it will:

- explore the uncharted innermost regions of our Solar System,
- study the Sun from close-up: 45 solar radii (31.3 million km),
- hover over the surface for long-duration, detailed observations by tuning its orbit for its perihelion speed to match the Sun's 27-day rotation rate;
- provide images of the Sun's polar regions from latitudes of up to 38°.

The scientific goals of the Solar Orbiter are to:

- determine in situ the properties and dynamics of plasma, fields and particles in the near-Sun heliosphere,
- investigate the fine-scale structure and dynamics of the Sun's magnetised atmosphere, using close-up, high-resolution remote sensing,





– identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere, using synchronised passes,
– observe and fully characterise the Sun's polar regions and equatorial corona from high latitudes.

The underlying basic questions that are relevant to astrophysics in general are:

– why does the Sun vary and how does the solar dynamo work?
– what are the fundamental physical processes at work in the solar atmosphere and heliosphere?
– what are the links between the magnetic field-dominated regime in the solar corona and the particle-dominated regime in the heliosphere?

In particular, Solar Orbiter will allow us to:

– unravel the detailed working of the solar magnetic field as a key to understanding stellar magnetism and variability,
– map and describe the rotation, meridional flows and magnetic topology near the Sun's poles, in order to understand the solar dynamo,
– investigate the variability of the radiation from the far side of the Sun and over the poles,
– reveal the flow of energy through the coupled layers of the atmosphere, e.g. to identify the small-scale sources of coronal heating and solar-wind acceleration,
– analyse fluctuations and wave-particle interactions in the solar wind, in order to understand the fundamental processes related to turbulence at all relevant scales in a tenuous magnetofluid,
– understand the Sun as a prolific and variable particle accelerator,
– study the nature and global dynamics of solar eruptions such as flares and coronal mass ejections, and their effects on the heliosphere ('space weather and space climate').

The near-Sun measurements combined with simultaneous remote-sensing observations of the Sun itself

Solar Orbiter Scientific Instruments						
Instrument		*Measurements*	*Specification*	*Mass (kg)*	*Power (W)*	*Data (kbit/s)*
SWA	Solar Wind Plasma Analyser	Thermal ions and electrons	0-30 kev/Q 0-10 keV	6	5	5
RPW	Radio & Plasma Analyser	AC electric and magnetic fields	μV/m - V/m 0.1 nT - μT	10	7.5	5
CRS	Radio Sounding	Wind density and velocity	X-band and Ka-band	0.2	3	0
MAG	Magnetometer	DC magnetic field	to 500 Hz	1	1	0.2
EPD	Energetic Particle Detector	Solar and cosmic ray particles	Ions and electrons 0.1-10 MeV	4	3	1.8
DUD	Dust Detector	Interplanetary dust particles	10^{-16} - 10^{-6} g	1	1	0.05
NPD	Neutral Particl Detector	Neutral hydrogen and atoms	0.6 - 100 keV	1	2	0.3
NED	Neutron Detector	Solar neutrons	e > 1 MeV	2	1	0.15
VIM	Visible-light Imager and Magnetograph	High-resolution disc intensity & velocity; polarimetry	Fe 630 line	26	25	20
EUS	EUV Imager and Spectrometer	Imaging and diagnostics of transition region and corona	EUV emission lines	22	25	17
EXI	EUV Imager	Coronal imaging	He and Fe ion lines	36	20	20
UVC	UV/visible coronagraph	Imaging and diagnostics of the corona	Coated-mirror coronagraph	17	25	5
RAD	Radiometer	Solar constant	Total solar irradiance	4	6.5	0.5

will allow the spatial and temporal variations to be untangled during the orbiter's sychronised passages. They will allow us to understand the characteristics of the solar wind and energetic particles in close linkage with the plasma conditions where they are created on the Sun. By approaching as close as 45 solar radii, it will view the atmosphere in unprecedented detail (35 km per pixel). Solar Orbiter will return images and data from the polar regions and the far side of the Sun – inaccessible to us on Earth.

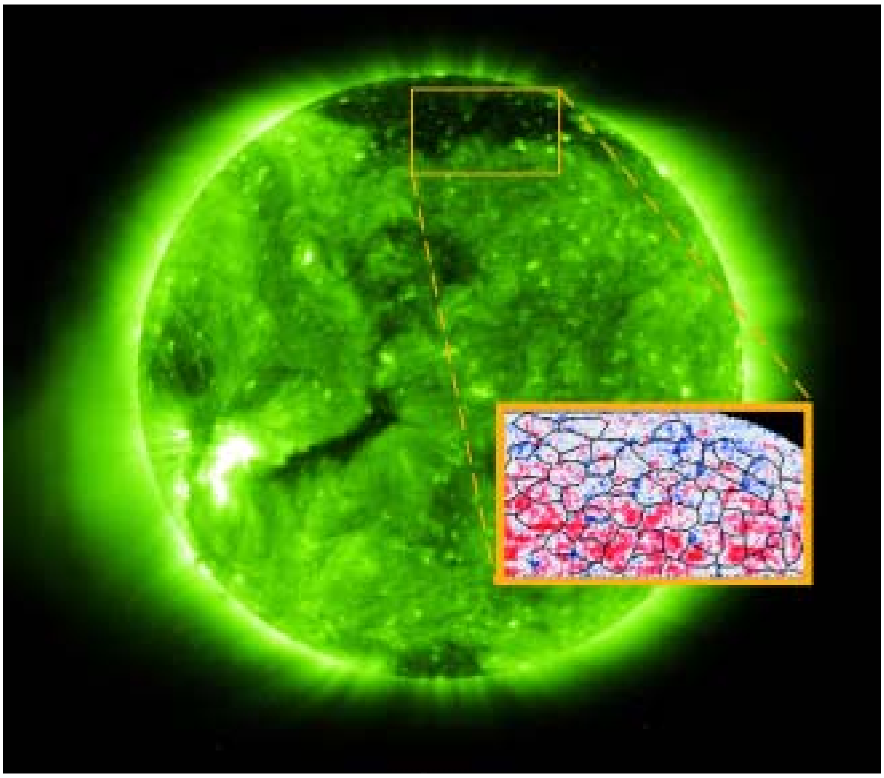
Solar Orbiter will achieve its wide-ranging aims with a suite of sophisticated instruments. Owing to its proximity to the Sun, the instruments can be smaller than on observatories, such as Soho, orbiting much further out.

The spacecraft design will benefit from technology developed for BepiColombo (such as Solar Electric Propulsion), allowing such an ambitious project to be carried out as a Flexi mission. SEP in conjunction with multiple planetary swingbys will deliver Solar Orbiter into an orbit with a perihelion of 45 solar radii and period of 149 days after only 2 years. Several Venus swingbys during the nominal 5-year mission will increase the orbit's inclination to 30° with respect to the solar equator. A mission extension of about 2 years would allow an increase to 38°.

The spacecraft will be 3-axis stabilised and always Sun-pointed. Given the extreme thermal conditions – 25 times harsher than at Earth's distance – the craft's thermal design was considered in detail during the assessment study.

Satellite configuration:
1.20x1.60x3.00 m box-shaped bus with instruments viewing Sun through thermal shield. Payload Module of CFRP at Sun end; Service

Soho observations of the regions where the solar wind is created illustrate the need for high-latitude observations and the potential for linking remote-sensing and in situ measurements of the surface and solar wind. The green image shows the extreme-UV Sun (Soho/EIT) with the polar coronal holes clearly visible. The inset Soho/SUMER Doppler images (Ne VIII) show blue- and red-shifted plasma flows; black lanes mark the supergranular network boundaries. The outflowing solar wind (blue-shifts) clearly originate in the network cell boundaries and junctions. This is an intriguing result, but as Doppler shifts can be measured only close to the line-of-sight, instruments need to fly well above the ecliptic plane to obtain a thorough understanding of the polar outflow of the high-speed solar wind. In addition, the distribution of the solar-wind outflow regions should be imprinted on the higher solar wind, which can be confirmed only by in situ measurements.



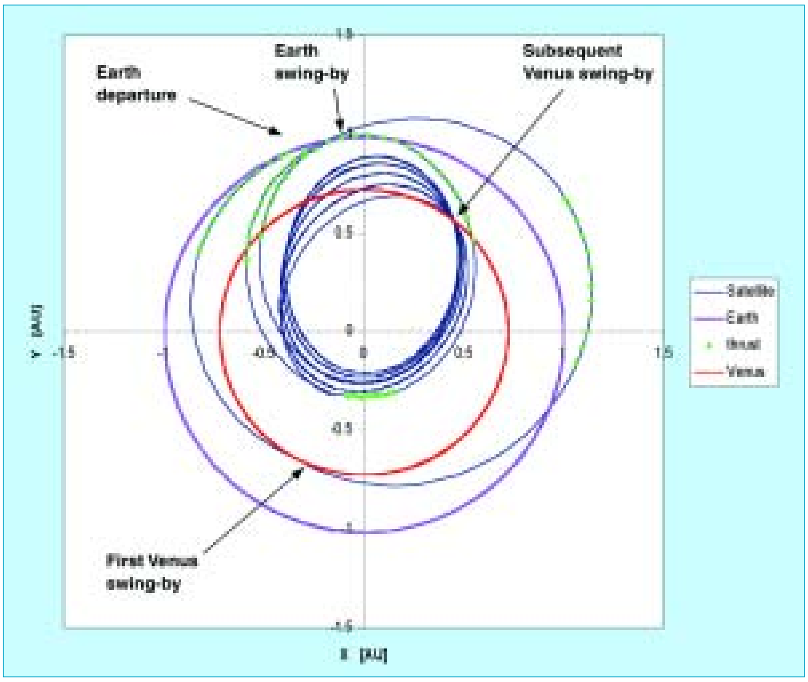
Module of aluminium honeycombe at other. Central cylindrical thrust tube.

Thermal control: to cope with 0.21-1.2 AU solar range. Thermal shield at Sun-end sized to shadow bus walls, HGA and solar array mechanisms: 3 titanium & 15 MLI layers, backed by 15 further MLI layers. Surface finishes, heaters, MLI, heat-pipes.

Attitude/orbit control: SEP by four 0.15 N plasma thrusters; Sun-pointing (stability better than 3 arcsec per 15 min) 3-axis stabilisation by four 4 Nms reaction wheels & star tracker. Initial Sun acquisition by gyros, coarse Sun sensors and redundant sets of six 5 N hydrazine thrusters.

Power system: twin 3-panel solar wings (28 m² generating 6.2 kW at 1 AU) mounted on bus side, jettisoned after SEP thrusting. Tilting 10 m² arrays on bus top provide power for observing mission

Communications: 1.5 m-diameter 2-axis steerable Ka-band high-gain antenna on 2.0 m boom to return 750 kbit/s at 0.6 AU Earth distance; X-band low-gain antennas for TC/TM. 75 kbit/s science data stored on 240 Gbit SSR, downlinked only when Sun distance >0.5 AU (thermal requirements). Controlled from ESOC via Perth 35 m station.



Solar Orbiter's path. The 22-month cruise phase uses Venus flybys and SEP thruster firings to establish the 0.2x0.9 AU operational orbit. During the 35-month, 7-orbit operational phase, Venus encounters increase inclination to 30°. The 27-month extended mission uses two Venus swingbys over 6 orbits to reach 38°.

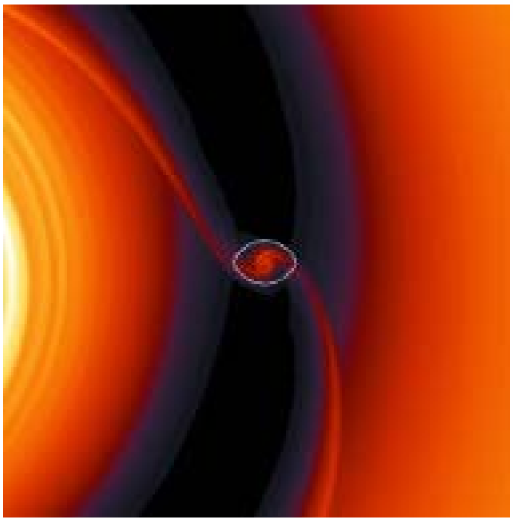
Darwin

Planned achievements: first detection and analysis of Earth-like planets, search for possible biospheres
Launch date: under development for flight beyond 2013
Mission end: nominally after 5 years; 10-year extended mission possible
Launch vehicle/site: Ariane-5 from Kourou, French Guiana
Launch mass: about 4.2 t for 8 spacecraft
Orbit: planned halo orbit around L2 Lagrangian point
Principal contractors: to be selected

The Darwin Infrared Space Interferometer is being developed to search for Earth-like planets orbiting other stars. It is a Cornerstone mission but lies beyond the current 2013 horizon of approved missions; it may be combined with NASA's Terrestrial Planet Finder.

Darwin's goal is to detect other terrestrial worlds, analyse their atmospheres and determine if they can support life as we know it. It will also interferometrically image objects in the thermal-IR with unprecedented resolution.

In its current configuration, Darwin consists of six 1.5 m-dia free-flying interferometric telescopes transmitting their light to a central beam-combining spacecraft. The beam-combiner carries two optical systems: one for Michelson imaging at very high spatial resolution, and one for 'nulling' interferometry. Nulling uses the wave nature of light to extinguish the light from a star, revealing any faint close companions normally hidden in the glare. Darwin can analyse the light from Earth-like planets at interstellar distances of up to 25 pc. The spectrum will show if a planet is benevolent to life, including the detection of a possible biosphere. A separate power and communication satellite flying close by allows the telescope and beam-combiner spacecraft to be passively cooled to < 40 K to increase sensitivity.

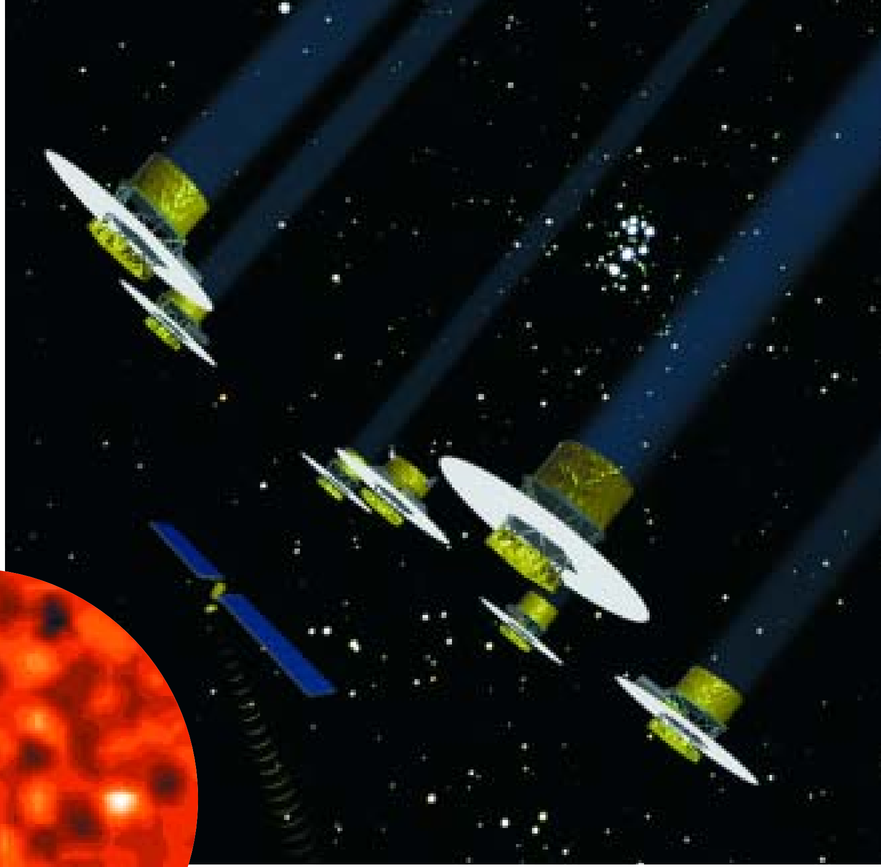


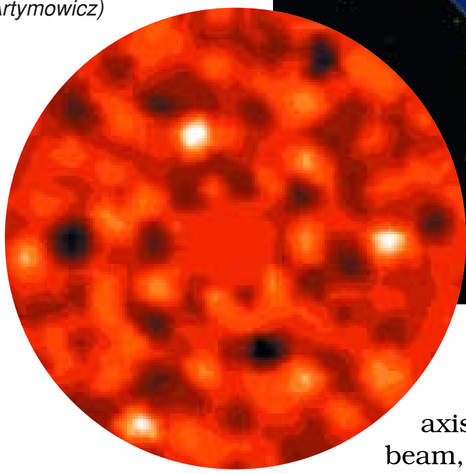
Darwin would orbit around the L2 Lagrangian point of the Earth-Sun system, 1.5 million km from Earth in the anti-Sun direction. For thermal reasons, the observing zone is a 40° cone around the anti-Sun direction. Control is by mN and µN thrusters, holding the inter-satellite precision with cm accuracy. The control system relies on high-precision laser metrology (~ 8 nm rms), and the tracking of fringes in a separate channel at ~2 µm. The array baselines are 50-250 m for planet-finding and 0.5-1 km for imaging.

The central questions to be addressed by Darwin are:

– how unique is the Earth as a planet?

Right: Darwin would use six telescope-spacecraft feeding their observations to a central combining-spacecraft. A separate communications satellite provides the link with Earth.
Inset: a simulated Darwin observation of our inner Solar System as viewed from a distance of 10 pc. Venus is at the top, Earth to the right and Mars at the bottom. (B. Mennesson)
Left: observing the gap created by a planet in a star's accretion disc is a prime target for Darwin. (P. Artymowicz)





– how unique is life in the Universe?

To answer these questions fully, it is necessary to:

– survey a significant sample of nearby stars for Earth-size planets
– directly detect planets within the 'habitable zone', i.e. the orbital region around a star where water is liquid, and determine the planets' orbital characteristics by repeating the observations several times
– observe the spectrum of the planet (does it have an atmosphere, what is the effective temperature and total flux?) and estimate its diameter
– determine the atmosphere's composition and search for H_2O, CO_2 and O_3/O_2.

Detecting an Earth-size planet circling a nearby star has been impossible so far because of the 10^9 difference in brightness at visible wavelengths. Even at IR, where the planet's thermal emission increases and the star's emission decreases, the contrast is still 10^6-10^7. The thermal-IR flux from an Earth-like planet at 10 pc is only 3 or 4 photons $m^{-2}\ s^{-1}$ in the whole range of spectroscopic interest (4-20 μm). Nulling interferometry applies phase shifts between different telescopes in an interferometric array to create destructive interference on the optical axis of the combined beam, accompanied by constructive interference a small angle away. We can search for planets in the 'habitable zone' by positioning the central star under this null and the zone where H_2O would be liquid under the peaks.

Many of the fundamental processes in the Universe are best studied at IR wavelengths. The 4-20 μm range is relatively free of obscuration by cold dust, and is instead a very good probe of dust warmer than 100 K. Spectroscopy at these wavelengths can characterise the chemical composition of many objects. Darwin will be able to resolve objects down to the milli-arcsecond scale, equivalent to a resolution of 400 000 km at the 4.26 light-year distance of the nearest star to our Sun. This means that Darwin can see the bands swept clean by condensing planets in the accretion discs around stars. A detailed study of the planet-forming process is extremely important and would complement the planet-finding element of the mission.

SMART-2, planned for 2006, will demonstrate technologies for LISA and Darwin, including inter-satellite metrology and control.

Acronyms & Abbreviations

Ah: amp-hour
AIT: Assembly, Integration & Test
AOCS: attitude and orbit control system
ASI: Agenzia Spaziale Italiana
AU: Astronomical Unit (149.5 million km)

BOL/EOL: Beginning of Life/End of Life
BSR: Back Scatter Reflector

CCD: Charge Coupled Device
CCSDS: Consultative Committee on Space Data Systems
CEA: Commissariat à l'Energie Atomique (France)
CEN: Centre d'Etudes Nucleaires (France)
CESR: Centre d'Etude Spatiale des Rayonnements (France)
CETP: Centre d'étude des Environnements Terrestre et Planétaires (France)
CFD: computational fluid dynamics
CFRP: carbon-fibre reinforced plastic
CNES: Centre National d'Etudes Spatiales (France)
CNRS: Centre National de la Recherche Scientifique (France)
CRPE: Centre de Recherche en Physique de l'Environnement terrestre et planetaire (France)
CSG: Centre Spatial Guyanais

DLR: Deutsche Forschunganstalt für Luft- und Raumfahrt (Germany)
DSP: Digital Signal Processor

EAC: European Astronaut Centre (ESA)
ECLSS: Environmental Control and Life Support System
ECU: European Currency Unit
EGSE: electrical ground support equipment
EIRP: equivalent isotropically radiated power
EOL/BOL: End of Life/Beginning of Life
ESA: European Space Agency
ESOC: European Space Operations Centre (ESA)
ESTEC: European Space Research and Technology Centre (ESA)
EUV: Extreme Ultraviolet

FIR: Far-Infrared
f.l.: focal length
FM: Flight Model
FOV: field of view
FWHM: full width at half maximum

GaAs: gallium arsenide
GEO: geostationary
GN_2: gaseous nitrogen
GOX: gaseous oxygen
GPS: Global Positioning System
GSOC: German Space Operations Centre
GTO: geostationary transfer orbit

HGA: High-Gain Antenna

IABG: Industrieanlagen-betriebsgesellschaft GmbH
IAS: Institut d'Astrophysique Spatiale (France)
IAS: Istituto di Astrofisica Spaziale (Italy)
IFOV: Instantanaeous Field of View
INTA: Instituto Nacional de Tecnica Aeroespacial (Spain)
IR: infrared
IRFU: Swedish Institute of Space Physics
ISS: International Space Station
IUE: International Ultraviolet Observatory
IWF: Institut für Weltraumforschung (Austria)

JEM: Japanese Experiment Module (ISS)

LEO: low Earth orbit
LHCP: left-hand circular polarisation
LN_2: liquid nitrogen
LOX: liquid oxygen
LPCE: Laboratoire de Physique et Chimie, de l'Environnement (France)

mas: milliarcsec
MDM: multiplexer-demultiplexer
MGSE: mechanical ground support equipment
MMH: monomethyl hydrazine
MOS: Metal Oxide Semiconductor
MPAe: Max-Planck-Institut für Aeronomie (Germany)
MPE: Max-Planck-Institut für Extraterrestrische Physik (Germany)
MPI: Max-Planck-Institut (Germany)
MPK: Max-Planck-Institut für Kernphysik (Germany)
mrad: milliradian
MSSL: Mullard Space Science Laboratory (UK)
MW: momentum wheel

N_2O_4: nitrogen tetroxide
NASA: National Aeronautics and Space Administration (USA)
NASDA: National Space Development Agency of Japan
NIR: Near-Infrared
NOAA: National Oceanographic & Atmospheric Administration (USA)
NRL: Naval Research Lab (USA)
NTO: nitrogen tetroxide

OBDH: onboard data handling
OSR: optical solar reflector

PI: Principal Investigator
PMOD: Physikalisch-Meteorologisches Observatorium Davos (Switzerland)
PMT: photomultiplier tube
PN: positive-negative

RAL: Rutherford Appleton Lab (UK)
RCS: reaction control system
RHCP: right-hand circular polarisation
RTG: Radioisotope Thermoelectric Generator
RW: reaction wheel
Rx: receive

SA/CNRS: Service d'Aeronomie du Centre National de la Recherche Scientifique (France)
SAO: Smithsonian Astro-physical Observatory (USA)
Si: silicon
SNG: satellite news gathering
SRON: Space Research Organisation Netherlands
SSPA: solid-state power amplifier
SSR: solid-state recorder
STM: Structural and Thermal Model

TC: telecommand
TT&C: telemetry, tracking and control
TWTA: travelling wave tube amplifer
Tx: transmit

UV: ultraviolet

VSAT: very small aperture terminal