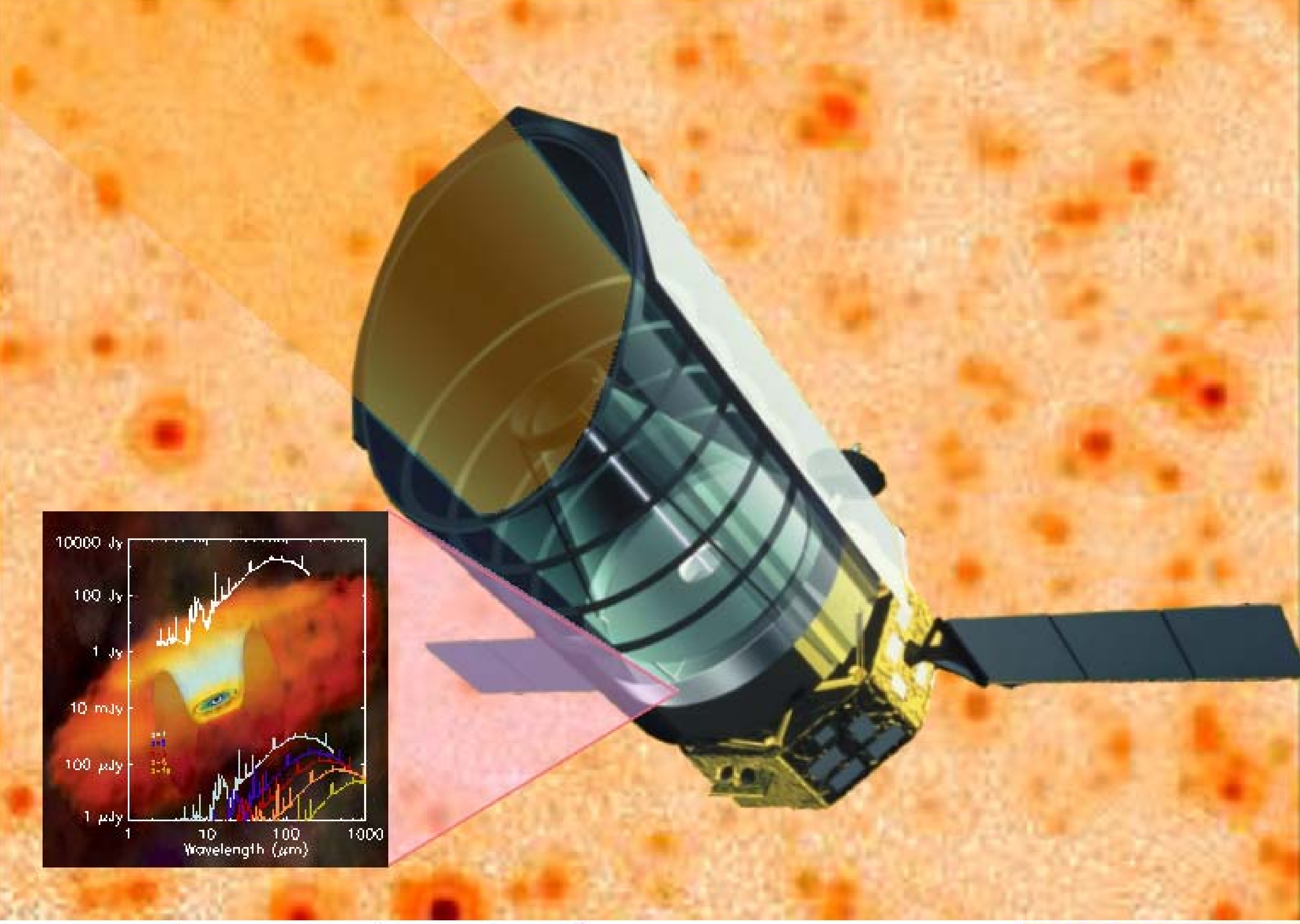
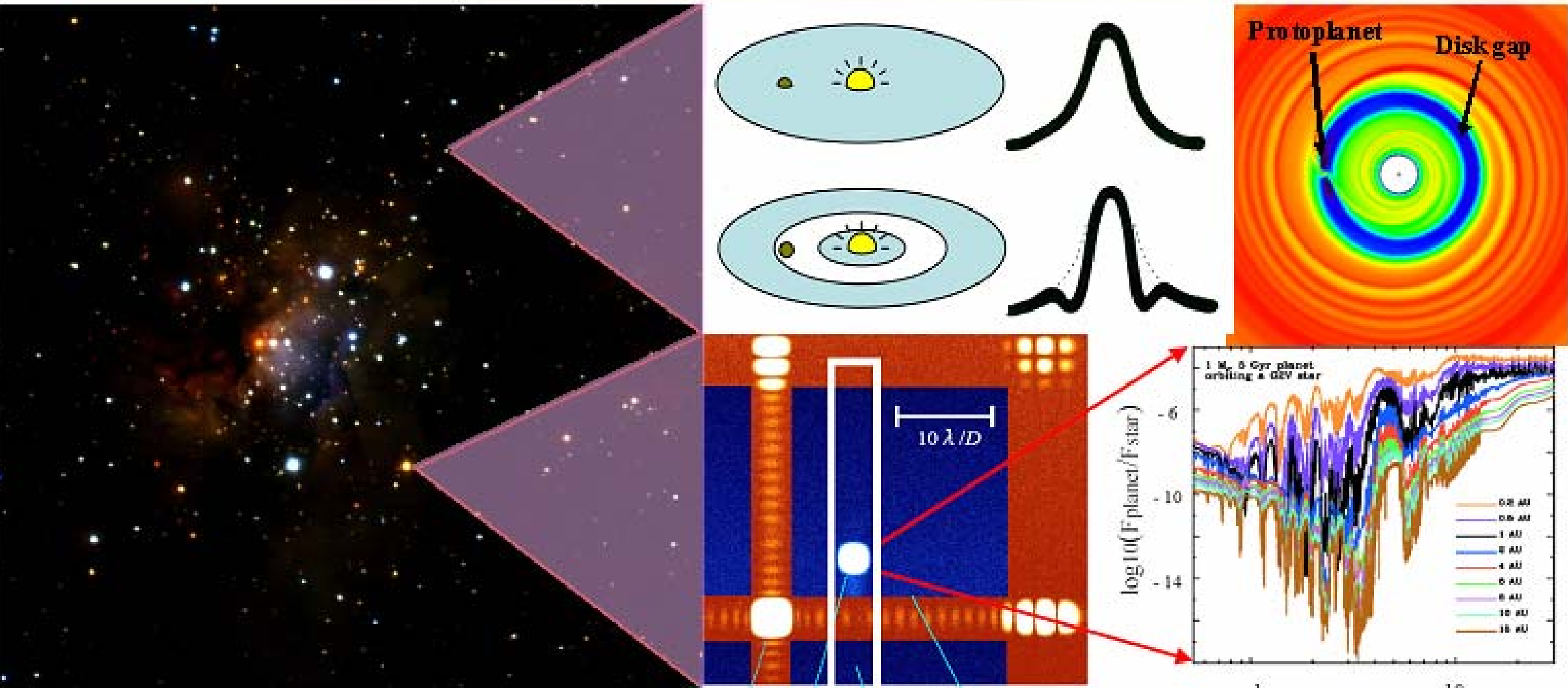
SPICA

A Cosmic Vision Proposal for a Joint JAXA/ESA Mission to Discover the Origins of Planets and Galaxies





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The background image is one of the Spitzer GOODS-S MIPS 24 mm deep extragalactic survey fields, which is available from the NASA Spitzer Science Centre:
http://data.spitzer.caltech.edu/popular/goods/Documents/goods_dr3.html

The foreground image shows an artists impression of the SPICA spacecraft with the thermal shield cut away to show the telescope assembly (ISAS/JAXA)

To the left of the spacecraft we show the redshifted spectrum of a typical starburst galaxy M82, (RAL) superimposed on an artists impression of a dusty torus surrounding an active galactic nucleus (NASA/CXO).

Bottom left we show an obscured galactic star cluster taken in the near infrared (J, H, K composite image) using the LIRIS instrument on the William Herschel Telescope (Image kindly provided by the joint CSIC and IAC MASGOMAS project)

To the right we show how SPICA will use high resolution MIR spectroscopy to determine the structure of gaseous disks – upper (NAOJ) - and a coronagraph to image and take spectra of young planets - bottom (ISAS/JAXA).

SPICA: A Joint JAXA/ESA Mission to Discover the Origins of Galaxies, Stars and Planets

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Executive Summary

From the very start of modern astronomy the question of how the Universe has come to look as it does has dominated observational and theoretical astrophysics. And yet, 160 years after the observation and description of spiral nebulae, later identified as galaxies, by Lord Rosse, and 100 years after the first mathematical description of star and planet formation by Sir James Jeans, our understanding of how galaxies, stars and planets form and evolve is still far from complete. A full understanding of these processes is only really possible with observations across that part of the electromagnetic waveband where the objects emit most of their radiation as they form and evolve. Visible and near infrared starlight makes up only half the radiation from a typical galaxy; the other half is emitted in the mid to far infrared (~5-200 µm – here-in-after MIR/FIR) range from the dust and gas in the interstellar medium which absorbs and re-emits the starlight as thermal continuum radiation and fine structure lines. As stars and planets form they are cocooned in regions of dust and gas which cool through a network of fine structure lines predominately in the MIR/FIR. Dust also obscures the central engines of active galactic nuclei (AGN) which are suspected to be important in the formation of galaxies, and it is only in the MIR/FIR that we can probe the nature of galaxies at an early stage of their evolution. It is in the MIR/FIR waveband, then, that we must observe in order to trace star formation over the history of the Universe and probe the formation and evolution of stars and planets in our own galaxy.

Observations in the MIR/FIR are difficult because instruments and telescopes must be cooled to cryogenic temperatures to achieve high sensitivity, and, for much of the range, can only be made from space-borne facilities. For these reasons progress has been slow, with only four small observatories operational in the past quarter of a century offering observers limited spatial resolution and sensitivity. In the next decade the Herschel mission, with a 3.5-m 80-K telescope, will provide greatly increased spatial resolution with modest increases in sensitivity over the FIR (57-210 µm) band, and JWST, with a ~6-m 45-K telescope, will provide a leap in both spatial resolution and sensitivity in the MIR up to 28 µm. Coverage of the full MIR/FIR band with high sensitivity and spatial resolution will still not have been achieved. It is here that the proposed Japanese mission SPICA (SPace Infrared telescope for Cosmology and Astrophysics) enters the picture, as it will have the same size telescope as Herschel (3.5 m), but cooled to < 5 K thus removing its self emission.

SPICA offers an improvement in sensitivity over Herschel by two orders of magnitude and observations over the full MIR/FIR range with sophisticated imaging, spectroscopic and coronagraphic instruments. The huge increase in sensitivity will allow SPICA to make photometric images in a few seconds that would take Herschel hours and to take the full FIR spectrum of an object in one hour that it would take Herschel several thousand hours to accomplish. This sensitivity, combined with a wide field of view and coverage of the full MIR/FIR waveband, will revolutionise our ability to determine the nature of the thousands of objects that Herschel, JWST, and SPICA, will discover in photometric surveys. The MIR capabilities of SPICA will extend the work of JWST by covering a greater wavelength range, providing higher spectral resolution (R~30000) and wide field medium spectral resolution (R~200) spectrophotometry.

The SPICA observatory will address directly three of the four Cosmic Vision themes in the following way:

Theme 1: "What are the conditions for planet formation and the emergence of life?" Cosmic Vision calls for a mission that will **"place the Solar System into the overall context of planetary formation, aiming at comparative planetology"** and **"Search for planets around stars other than the Sun"**. SPICA will make images and the first uncontaminated MIR spectra of young massive planets using its advanced coronagraph which provides a contrast of 10^{-6} and an ability to image directly young massive planets as close as 9 AU at 10 parsec – this means we will see planets in the process of formation at the equivalent of the orbit of Saturn.

There is also the call to, **"Investigate star-formation areas, proto-stars and proto-planetary disks and find out what kinds of host stars, in which locations in the Galaxy, are the most favourable to the formation of planets"** and **"Investigate the conditions for star formation and evolution"**. SPICA's FIR photometric sensitivity will allow us to detect the photospheres of stars out to many kiloparsecs, and therefore the presence of the faintest possible traces of dust at temperatures not accessible in the MIR, giving us a unique and unbiased insight into which types of stars, and at what stage of evolution, have planets either formed or in the process of formation. With MIR spectral resolution equivalent to 20 km/s we will resolve the gas dynamics of proto-

planetary disks in hundreds of stars and, from FIR spectroscopy of the oxygen and water lines in the same disks, will see the first indications of the chemistry vital to the emergence of life.

Theme 2: "How does the Solar System work?" This theme calls for the study of asteroids and comets as they are **"the most primitive small bodies"** that can **"give clues to the chemical mixture and initial conditions from which the planets formed in the early solar nebula"**. SPICA's high sensitivity spectroscopy will allow the chemistry of comets and Kuiper Belt objects to be studied to an unprecedented level of detail. In particular it will provide the ability to detect water ice by observing the emission bands at 44 and 63 μm with high sensitivity. This will allow us to link our own "icy debris" to that seen around other stars and to probe the influence of ice on the agglomeration of dust, the formation of rocky planets and the origins of the terrestrial oceans.

Theme 4: "How did the Universe originate and what is it made of?" Here SPICA is ideally suited to study **"… star-formation activity hidden by dust absorption"** by tracing the solid state features of dust further into the past than ever before. The combination of MIR and FIR spectroscopy on SPICA is also essential to **"Trace the formation and evolution of the super-massive black holes at galactic centres – in relation to galaxy and star formation – and trace the life cycles of chemical elements through cosmic history"**. SPICA will be the first observatory with the ability to detect the MIR and FIR cooling lines out to the peak of star formation activity in the history of the Universe (z~1-2). It will do this for a wide range of galaxy types allowing a unique and unbiased view of galaxy evolution, the link between metallicity and star formation, and the relationship between starburst galaxies and active galactic nuclei.

Following on from the highly successful infrared survey mission AKARI, SPICA is planned for launch by JAXA on the H2A launcher in 2017 with a nominal five year mission lifetime orbiting at L2. The 3.5-m telescope and instruments will be cooled to < 5 K using a combination of high reliability mechanical coolers and passive radiative cooling giving a long lifetime and low launch mass for the mission. At least three focal plane instruments are proposed: an MIR instrument with broadband imaging and spectrographic capabilities to be developed by a Japanese/South Korean consortium; an MIR coronagraph to be developed by Japanese institutes and a (nationally funded) FIR imaging spectrometer to be developed primarily in Europe/Canada with possible contributions from Japan and the USA (NASA).

This proposal calls for ESA to assume a partner agency role in SPICA by making the following contributions:

SPICA Telescope Assembly: This at the heart of the mission and one of the enabling technologies for SPICA. The assembly includes the cryogenic telescope primary and secondary mirrors, the support structure for the mirrors and a focus adjustment mechanism for the secondary mirror. The mirrors and structural items will be fabricated from silicon carbide building on experience and heritage in Europe (e.g. Herschel, GAIA, ALADIN and SPICA breadboard mirrors) and Japan (e.g. AKARI and SPICA breadboard mirrors). The technical difficulty of achieving and verifying the SPICA telescope specifications is between the more relaxed Herschel telescope and the more demanding GAIA telescope. The estimated cost of this is 50 M€.
European SPICA Ground Segment: The scientific return from the mission can be significantly enhanced by two ESA contributions to the ground segment: the provision of downlink capacity from a ground station in Europe and the coordination and management of European science operations time (proposed to be 25% of the total) from a Science Operations Centre located at ESAC. The estimated cost of this is 12 M€.
Instrument Systems Engineering and Management: ESA can make a valuable contribution to the technical and programmatic success of the nationally funded FIR instrument by managing the acceptance and delivery of the instrument from ESA to JAXA and the management and negotiation of interfaces between the spacecraft and instrument in an analogous way to the ESA support for the MIRI instrument for JWST. The estimated cost of this is 8 M€.
SPICA Mission Support: Various inter-agency groups will be required to manage the overall programme between the two agencies, to oversee instrument development, and manage the numerous engineering tasks. ESA proposed engineering and managerial support for these groups is estimated at 4 M€.

For a total contribution of ~75 M€ ESA will take a prominent role in SPICA so offering the European community observing time in a world leading observatory that will unlock the processes of galaxy and planet formation and evolution. SPICA will also provide the technological springboard for future, more ambitious, interferometer missions, such as FIRI, which will finally provide direct detection of exo-Earths and the kind of spatial resolution in the FIR that SPICA and JWST achieve in the MIR.

1. Introduction

1.1 Overview

This proposal is to invite ESA to become a partner in the forthcoming Japanese-led Space Infrared telescope for Cosmology and Astrophysics, SPICA. This mission will allow a major breakthrough in detection sensitivity in the 5 to 210 μm waveband (here-in-after MIR/FIR) which will revolutionise our understanding of how galaxies, stars and planets form and evolve as well as the interaction between the astrophysical processes that have led to the formation of our own Solar system and the emergence of life on Earth. In this proposal we will demonstrate the unique ability of SPICA observations to probe galaxy, star and planetary system formation as well as the evolution of dust and gas in the interstellar medium of our own and distant galaxies. We believe that ESA is in a unique position to become a partner in this mission through the provision of a ceramic 3.5 m telescope (such as provided for the Herschel Space Observatory); ground segment expertise, and support to a nationally funded European consortium which plans to provide one of the core focal plane instruments for SPICA.

1.2 The SPICA Mission in Context

Since the advent of observational astronomy in the MIR/FIR wavelength band with IRAS [1] and the KAO [2], and after the success of the infrared space observatories ISO, Spitzer and AKARI [3,4,5], it has become increasingly clear that we can only fully understand the evolution of the Universe and of all its constituent parts by observing the MIR/FIR emission from dust and gas. In order to properly observe between ~ 5 and 210 μm it is necessary to use spaceborne infrared telescopes as airborne or mountain top observatories can only cover restricted waveband ranges at limited sensitivities. It is also necessary that any MIR/FIR observatory is cooled to temperatures at which the self-emission from the telescope and instruments does not overwhelm the signal from astronomical sources. To give uninterrupted access to the whole waveband a telescope temperature < 5 K is required and all space observatories to date (IRAS, ISO, Spitzer and AKARI) have used liquid helium (LHe) to cool their telescopes and instruments to below ~5 K. This has necessitated the use of large quantities of liquid cryogen to cool the telescopes, resulting in aperture sizes of less than 1 metre. To date, therefore, our ability to characterise the cold and dusty Universe has been limited by poor spatial resolution and low sensitivity relative to other wavelength ranges, despite the development of highly sensitive detectors, especially in the 5-30 μm band.

This situation will be improved in the coming decade with the advent of the Herschel Space Observatory[6] with an 80-K 3.5 m telescope operating from 57 to 700 μm and the James Webb Space Telescope (JWST)[7] with a 45-K, 25-m^2 telescope operating from 0.6 to 28 μm and diffraction limited at 2 μm. Herschel and JWST will represent a leap in our ability to observe in the MIR/FIR and, with JWST at least, come close to the spatial resolution and sensitivity limits obtained in the optical and sub-mm bands. However, both have drawbacks in terms of advancing our full understanding of the MIR/FIR Universe: JWST does not cover wavelengths longer than 28 μm; Herschel only starts coverage at 57 μm and, because of its relatively warm aperture, Herschel only gives a modest improvement in sensitivity compared to Spitzer, despite its superior imaging and spectroscopic capabilities.

To break through the sensitivity limitations of Herschel and the narrow wavelength coverage of JWST, the Japanese space agency (ISAS/JAXA) is proposing to build SPICA. This mission can be built within 10 years without major technical development, but will offer a breakthrough in sensitivity in the FIR region and will provide MIR capabilities to cover the MIR/FIR waveband within a single facility. SPICA will have a 3.5 m telescope actively cooled to below 5 K to remove all self emission, thus massively increasing the potential sensitivity in the FIR compared with Herschel. Furthermore, SPICA will employ mechanical coolers rather than cryogens giving it a long lifetime whilst still allowing a large mirror size. The telescope will be monolithic, like Herschel, and will in principle have a much cleaner point spread function than a deployable segmented mirror, allowing diffraction-limited performance across the full wavelength range. To take advantage of this low-background environment the instrument suite proposed will have wide field MIR and FIR imaging, medium to high spectral resolution MIR and FIR spectroscopy and a MIR coronagraph designed for imaging and spectroscopy of young Jupiter-like planets around nearby stars.

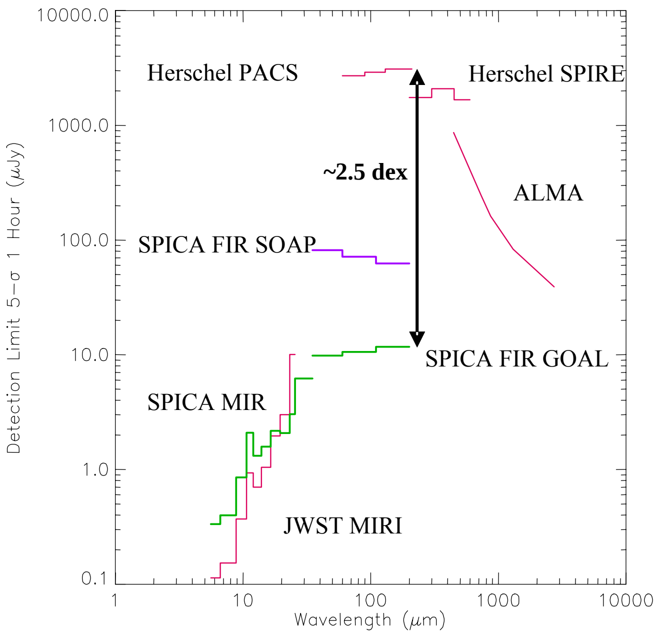


Figure 1 - Predicted photometric performance of SPICA (green and purple) compared to predecessor and complementary facilities (red) given as point source sensitivities in μJy for 5-σ in 1 hour over the bands shown indicatively as horizontal lines. Note the 2 ½ orders of magnitude increase in FIR photometric sensitivity compared to PACS that will be achieved using goal sensitivity detectors on SPICA. The figures here are raw sensitivity only. The effects of confusion, and their mitigation, are discussed later.

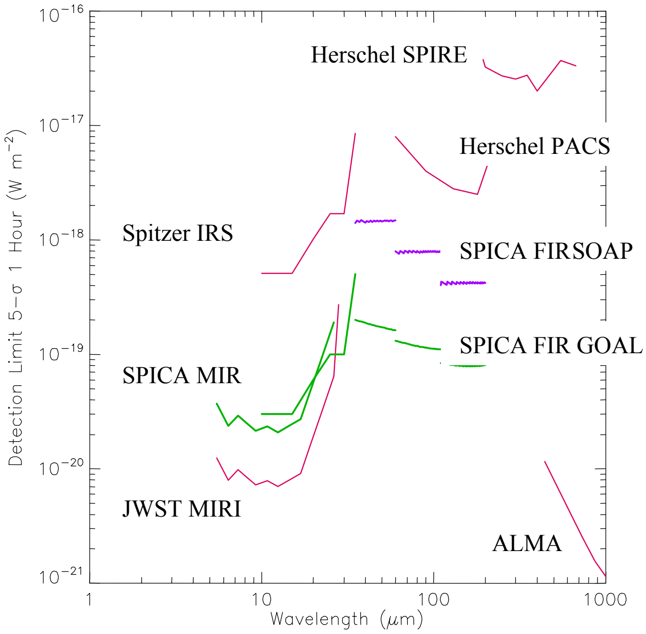


Figure 2 - Predicted spectroscopic performance of SPICA (green and purple) compared to predecessor and complementary facilities (red) given as single unresolved line sensitivity for a point source in W m^{-2} for 5-σ in 1 hour. For ALMA 100 km/s resolution is assumed as this is appropriate for extra-galactic sources. The SPICA MIR sensitivities are scaled by telescope area from the JWST and Spitzer IRS values respectively.

In order to place the potential performance of the SPICA mission in context, Figure 1 and Figure 2 show the wavelength coverage and estimated point source sensitivities for photometric and spectroscopic observations that will be possible with SPICA. Also shown in the same figures are the sensitivities of the predecessor (Herschel) and complementary facilities such as JWST[8] and ALMA[9] that will be in operation in the same time. In preparing these figures we have used publicly available sensitivities for Herschel, JWST and ALMA and have calculated the SPICA sensitivities using the same model formulation as used for JWST[8] and Herschel[10]. For the MIR range (5-37 μm) we assume state of the art performance (SOAP) Si:Sb or Si:As detectors as used on Spitzer and JWST. For the 35-210 μm wavelength range two possibilities are shown: SOAP performance based on a combination of Ge:Ga photoconductors and a development of the Herschel-PACS bolometer arrays; and Goal performance based on the development of Transition Edge Superconducting (TES) bolometer arrays based on devices used for the SCUBA-2 instrument on the JCMT[11] and development programmes ongoing in European institutes[12]. In §4 we discuss the technical readiness level of each detector technology and the development programmes required to achieve the goal performance.

It is clear from Figures 1 and 2 that a huge gain in sensitivity over Herschel can be achieved with SPICA even with SOAP detectors, especially when combined with the proposed large fields of view – see §4. With a well structured detector development programme it will be possible to deliver detectors with a far better performance and a commensurate leap in detection sensitivity that will, for the first time, place FIR observations in the same league as the sub-mm and MIR. In the MIR SPICA will have virtually the same sensitivity as the JWST but over a wider wavelength range enabling it to provide complementary instrument capabilities in the form of a wide field low/medium resolution (R~200) objective grism spectrometer, much higher spectral resolution (R~30000) to allow the gas dynamics of protoplanetary disks to be examined and an advanced coronagraph that will allow both imaging and spectroscopy of young gas giant planets in hundreds of nearby stars. In the next section we describe the scientific breakthroughs that these major advances in MIR/FIR capability will make possible.

2. Science with SPICA

One of the enduring themes of modern astrophysics has been to discover how and when the Universe came to look as it does today. In addressing this question we seek the solution to more detailed questions over how galaxies, stars and, importantly in our quest to understand how humans came to ask these questions at all, how planets form and life began. These questions are directly addressed in three of the themes of Cosmic Vision 2015-2025: "What are the conditions for planet formation and the emergence of life?"; "How does the Solar System work?"; "How did the Universe originate and what is it made of?" SPICA can explicitly, and uniquely, address each of these themes as it is only with highly sensitive MIR/FIR observations that we can directly observe star formation in distant galaxies, determine the relationship between dust enshrouded active galactic nuclei (AGNs) and starburst galaxies, follow the evolution of dust from formation to the formation of planets and probe the pre-biotic chemistry in the tenuous disks from which planets form.

In the rest of this section we first review the tools that observations in the MIR and FIR provide for the study of cold, obscured regions in our own and other galaxies where stars and planets are forming. We go on to detail the ground breaking discoveries that will be enabled by the SPICA mission starting with planetary formation, going through the formation and evolution of galaxies of all types and ending with speculation into the new science that always accompanies major increases in sensitivity. At the end of the section we summarise the scientific requirements for the mission that will enable this science and which will inform all aspects of the technical development of the mission.

2.1 A Critical Wavelength Region

The 5-210 μm spectral range is one of the richest windows of the electromagnetic spectrum emitted by astrophysical objects. It spans the wavelength range over which the largest proportion of the energy is emitted during the evolution of galaxies. It plays host to a variety of atomic/ionic forbidden transitions that, spanning a large range in excitation, ionization and density conditions, are among the best to trace gas excited from both stellar evolution processes as well as non-thermal processes. Radiation in the MIR/FIR, unlike the NIR, optical and UV light, is largely unaffected by the dramatic effects of dust extinction and includes many of the most prominent PAH and Silicate features and so can be used to trace star formation and AGN activity in both the local and the very distant Universe. It is also the range in which warm molecular gas found in AGN tori, shocks, stellar envelopes, x-ray illuminated regions, outflows and dense protostellar cores can be studied through the transitions of CO, OH, H_2O and molecular hydrogen.

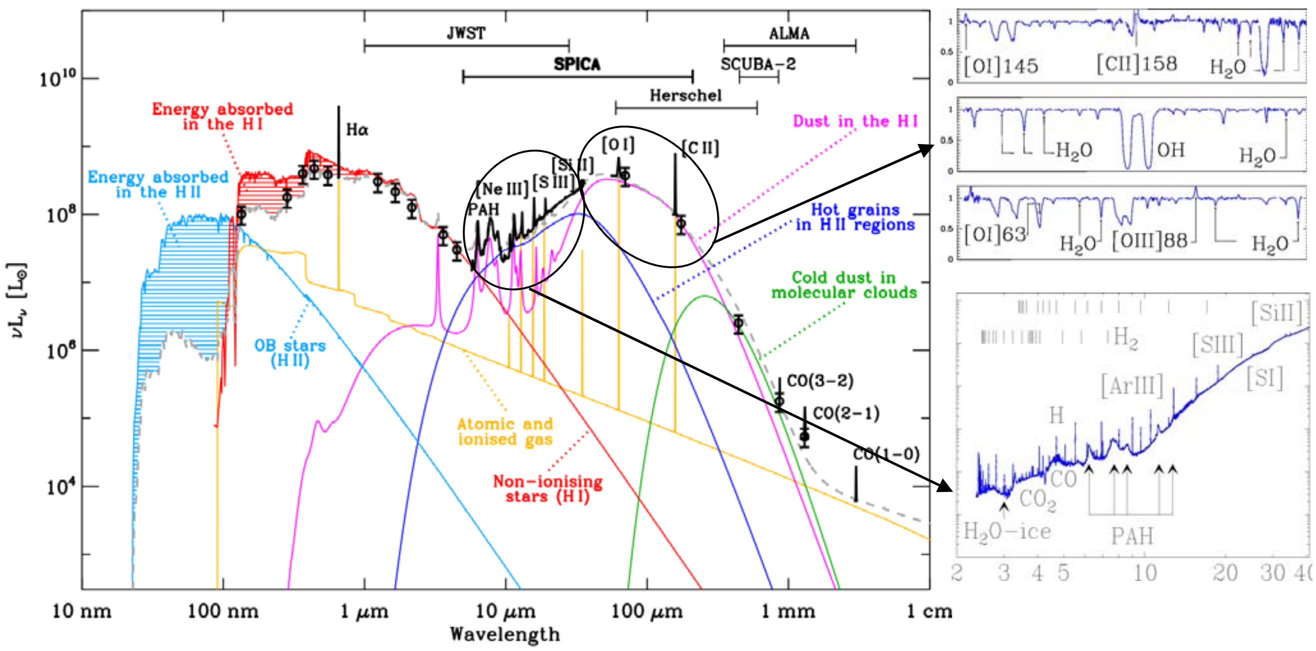


Figure 3 - A synthetic spectrum of a typical galaxy undergoing modest rates of star formation – similar to the Milky Way – showing the parts of the spectrum that will be covered by SPICA and contemporaneous facilities. The major importance and spectral richness of the mid to far infrared region is demonstrated by the detailed spectra from ISO shown to the right of the diagram [13, 14, 15].

Figure 3 shows the spectral energy distribution (SED), from x-ray to radio, of a typical galaxy that is undergoing modest star formation. The bulk of the radiated power is emitted in two "windows": the optical (i.e. starlight) and the MIR/FIR, where the dust in the interstellar medium absorbs and re-radiates the starlight. The fine structure lines from ions, atoms and molecular transitions play a critical role as gas coolants. This is due to their low excitation potentials and because they are not readily absorbed, they therefore drive the thermal energy balance in a large variety of physical conditions. The MIR/FIR transitions and spectral features illustrated in Figure 3 have an enormous diagnostic role to play in many key areas of astrophysics. They can discriminate between the emission of AGN and starburst regions in the evolution of galaxies, as they are able to trace the underlying spectrum responsible of the gas excitation. They trace dust obscured regions in protostellar environments, circumstellar and circumplanetary disks, as well as in hypothetical tori around nuclei of galaxies and they can trace the chemical evolution of the ISM in both our own and more distant galaxies.

As one moves to higher redshift, the UV/optical-NIR waveband shifts into the MIR/FIR, providing access to rest frame UV-optical spectroscopy which in turn traces the first phases of galaxy evolution through its main constituents: stars and accreting black holes. In this way the complete history of galaxy evolution can be written with a powerful and sensitive set of MIR/FIR spectra.

Within this proposal it is not possible to do justice to the vast range of scientific topics that SPICA can address. Rather we have taken the approach of highlighting the key areas where SPICA provides unique and essential observational insight. We start the story with the formation of planetary systems; we touch on mass loss from massive stars and the mechanisms of dust formation and evolution within our own galaxy before discussing the evolution of galaxies in the nearby universe, the relationship between AGNs and starbursts and high redshift evolution of galaxies; before finishing with a discussion of what new science such a major gain in sensitivity might uncover.

2.2 Planetary system formation: from gas and dust to planets; from ices to oceans

The study of star formation in our own Galaxy has been revolutionised by spectroscopic observations in the MIR/FIR, as it is only in this waveband that the neutral gas chemistry and gas/grain processes within the highly obscured stellar nurseries can be observed. The spectrometers on Herschel are expected to make further strides in our understanding of star formation but, to date, there has been little or no direct study of the role of MIR/FIR cooling lines in the formation of planetary systems, despite the obvious importance of, for instance, oxygen chemistry to the emergence of life. As we discuss below, SPICA will have the sensitivity to detect the lines from species such as O, OH and H_2O (both gas and ice) from proto-planetary gas disks in the early stages of planetary formation. In fact SPICA will have sufficient sensitivity to detect them in a volume sufficiently large to make the first unbiased study of the chemistry of disks around all spectral types of star. The huge increase in photometric sensitivity that SPICA will achieve in the FIR will also enable us to trace the presence of cool, dusty disks out to the furthest reaches of the Galaxy, answering directly questions over planetary formation as function of stellar type and age and providing a comprehensive inventory of stars with circumstellar debris disks that will be invaluable to future planet imaging facilities. In the nearest objects with circumstellar disks (such as Vega), SPICA's unique access to the FIR water ice features will allow us to map the "snowline" for the first time, giving a critical insight into the role of water ice in the formation and evolution of planetary systems.

Gas Disks: Most young stars are surrounded by accretion disks which are the likely progenitors of planetary systems. The physical and chemical conditions in protoplanetary disks set the boundary conditions for planet formation and an understanding of the formation and evolution of protoplanetary disks will finally link star formation and planetary science. Our current view of these objects states that disks evolve from gas–rich structures where only ~1% of the total mass is in the form of dust grains, to optically thin debris disks almost completely devoid of gas. Although the dust is relatively easily detected from photometric observations in the 20-100 μm range, very little is known about the gas phase. It seems clear that an abrupt transition from massive optically thick disks to tenuous debris disks occurs at $\sim10^7$ years[16] after the star enters the main sequence, by which time the majority of at least the giant, gaseous planets within a system must have formed. The disk is the major reservoir of key species with astrobiological relevance, such as water (both vapour and ices) and oxygen, to be found later in planets, asteroids and comets. But how the presence and distribution of these species relates to the formation of planets, and most particularly habitable planets with substantial amounts of water present, remains open to speculation without a substantial increase in observational evidence. Only an observatory with very high spectral sensitivity, such as SPICA, will be able to provide these observations.

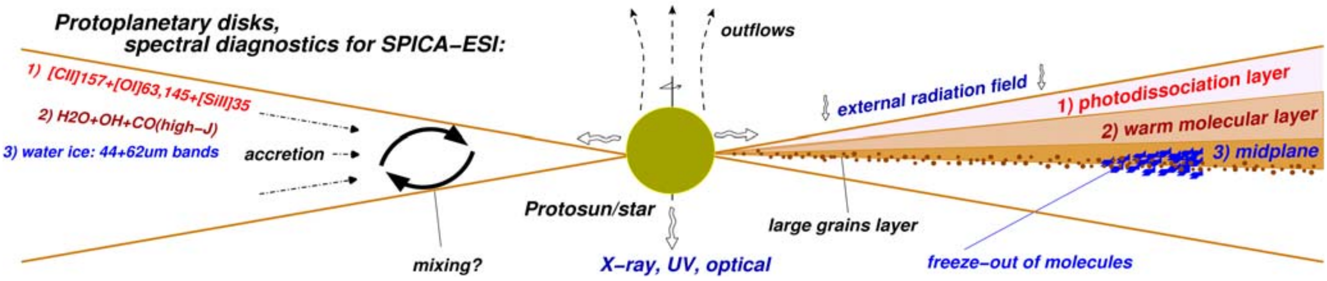


Figure 4 - Diagram showing where radiation arises from in a proto planetary disk and why the MIR/FIR and sub-mm together are essential to understanding the full picture of the role of gas disks in the formation of planetary systems and the primordial chemistry that leads to the emergence of life.

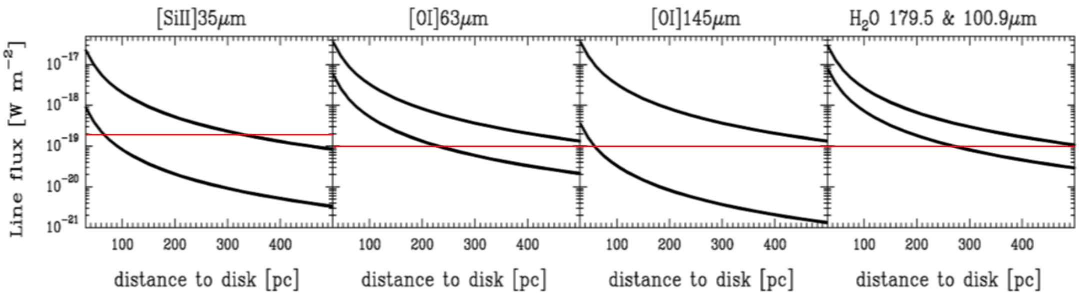


Figure 5 - Predicted maximum and minimum fluxes for significant MIR/FIR cooling lines for protoplanetary disks taken as a function of distance from the Sun (after Gorti and Hollenbach 2004 [18]). The red lines indicate the SPICA 5-σ 1 hour sensitivity limit

Standard disk models predict a "flared" structure for the disk geometry (see Figure 4) which allows the disk to capture a significant portion of the stellar UV and x-radiation even at large radii[17] boosting the MIR/FIR dust thermal emission, and sub-mm and FIR emission lines. Although widely observed from the ground, and to be observed with ALMA with extremely high spatial resolution, CO in itself is not a good tracer of the total amount of gas in the disk as it suffers from selective photodissociation at the irradiated surface and is depleted by condensation onto cold grains in the mid-plane. Water and OH thermal lines, however, are predicted to be the strongest coolants of the disk surface especially closer to the star (i.e. at high temperatures and densities), with line intensities comparable to those of the strong atomic fine structure lines of oxygen and other heavier metals[18]. In Figure 5 we show the predicted strengths of some of the most important cooling lines in the 20-210 μm region as a function of distance from the Sun under an optimistic and pessimistic case. With the high sensitivity of SPICA over this wavelength region we will be able to detect and characterise hundreds of proto-planetary gas disks, producing an extensive census of stellar and disk types that will give a critical insight into the conditions under which planets form and the conditions for life emerge. For the strongest lines in the 5-15 μm range, and at spot wavelengths at 17 and 28 μm to include all the H_2 ground state ortho and para rotation lines, SPICA will have a very high resolution spectrometer (R ~ 30 000) capable of resolving the Keplerian rotation in the line profiles and so characterising the physical and chemical parameters of gas disks as a function of radius.

Dust in Circumstellar Disks: Dust appears to be present at all stages of planetary system formation with the ratio of gas to dust, the amount of dust present, its temperature and its distribution evolving rapidly through the process of planetary formation [19, 20]. The processing and evolution of the dust in proto-planetary disks is key to understanding the formation and mineralogy of rocky, Earth-like, planets. For instance, it appears that in disks around intermediate mass, pre-main sequence stars, the dust in the inner regions of the disk (≤ 2 AU) can be more evolved. That is, it shows signatures of grain growth and crystallisation, whereas the dust in the outer region is often seen to be pristine and similar to the diffuse ISM dust[21]. This implies a strong radial dependence of the dust processing whereby the inner regions are dominated by the stellar radiation field, leading to grain heating and crystallisation, and by higher densities, leading to coagulation, whilst the outer regions remain largely unprocessed and carry the signature of the pre-stellar nebula from which the star formed. And yet in our own Solar system we see crystalline silicates present in comets that clearly originate from regions far from the zones where this processing must have occurred. Only with detailed mapping of the minerals of our own and distant circumstellar material will we be able to understand the evolutionary track that leads to this situation. The final stage of planetary system formation often appears to result in the formation of almost gas-free, dusty debris disks, perhaps resembling our own Kuiper belt (cool outer disk) and/or Asteroid belt (hot inner disk). These

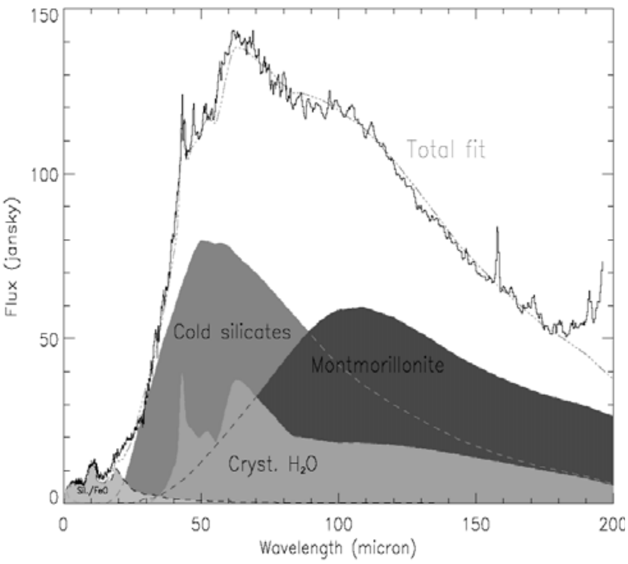


Figure 6: The ISO spectrum of the young star HD 142527 [22] showing the model components including the crystalline water ice features. Water ice can only be directly detected at these temperatures through the 44 and 63 μm emission features. SPICA will be able to take the equivalent spectra of objects at flux levels of ~1 mJy in one hour.

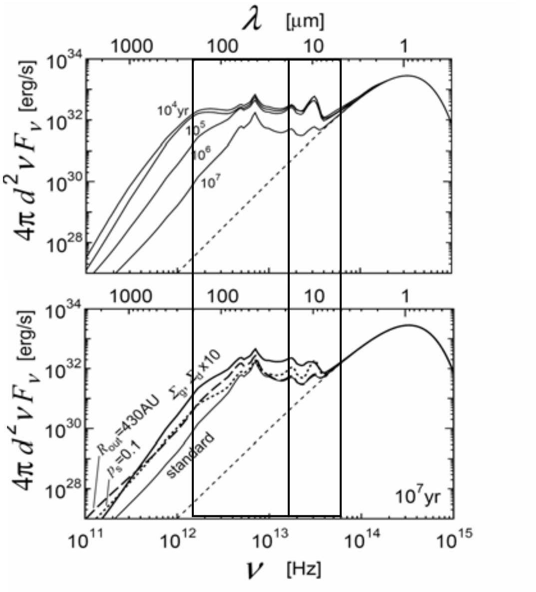


Figure 7: Predicted spectra of dust excesses from proto-planetary disks as a function of age -upper plot - and, for a given age disk, different dust size distributions and disk density profiles – lower plot[20]. The blue band shows the MIR coverage of JWST and the grey band the FIR coverage of SPICA

debris disks are thought to be formed of dust produced by the mutual collisions of planetesimals in the final stages of planetary formation and the "heavy bombardment" phase evidenced in the impact craters seen in all rocky Solar system planets. Images of the dust in debris disks, either seen in reflection or directly in the FIR or sub-mm, can show gaps and ring-like structures indicating the presence planets which "shepherd" the dust.

The ability of FIR spectroscopy to determine the mineral makeup of dusty disks in young stars is illustrated by the ISO spectrum of HD142527 shown in Figure 6. SPICA will be 100's of times more sensitive than ISO and so will see not only the young opaque objects like this, but will be able to trace the mineralogy of dust within disks at all stages of planetary system formation and, because of its full wavelength coverage, will probe both the cold and warm dust populations and emission features. SPICA will not only be able to determine the detailed mineralogy of the dust, but will also trace the variation in grain size distribution and temperature, which are both expected to evolve with disk age leading to a variation in the disk SED. This is demonstrated in Figure 7 where we can see that there is little predicted evolution of the MIR SED with disk age and a possible ambiguity in the MIR intensity between age and disk structure which is removed with observations in the FIR. The photometric capability of SPICA will enable the detection the photospheres of Vega-like stars out to many kiloparsecs and Solar type stars out to ~2 kiloparsecs (Figure 8), allowing the most complete survey of the existence of disks by stellar type to date. Taking the model SEDs and photometric detection limits together, we can see that SPICA offers a major step forward in our ability to determine the presence and evolutionary state of circumstellar disks that cannot be achieved in the MIR and sub-mm alone.

In nearby systems we will be able to image disks directly (see Figure 9) to examine their structure. This has been most readily observed so far using ground based sub-mm facilities such as the JCMT, CSO and IRAM, and ALMA will undoubtedly add a great deal to the subject. However, it is only in the MIR/FIR that we will be able to trace the variation in dust mineral content, size distribution and temperature and so, in a few examples, we will be able to directly trace the mineral content and grain size distribution as a function of radius to compare these, together with the spectra of comets, asteroids and TNOs within our own Solar system, with the 100s of spatially unresolved objects which SPICA will be able to observe. In more distant stars SPICA will be able to use MIR coronagraphy to image and take spectra of the inner parts of many more disks. It will also be able to take the spectrum of the dust across the full MIR/FIR waveband. SPICA's high photometric sensitivity will allow the detection of as little as 10^{-4} Lunar mass of dust at ~100 K out to 10's of parsecs; this is approximately the mass of our own Zodiacal cloud. In summary, using the full capabilities of SPICA we will reveal for the first time the detailed processes that lead eventually to the formation of Earth-like planets.

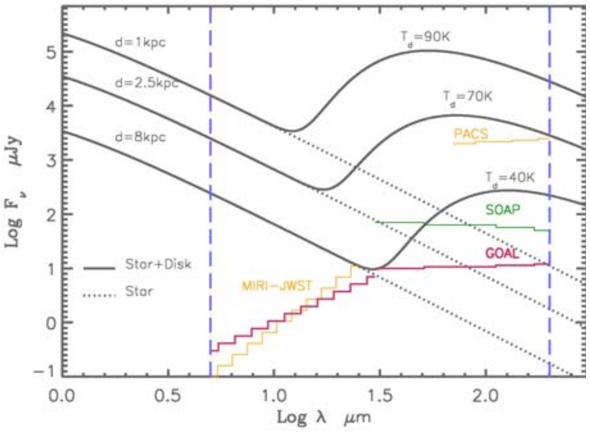


Figure 8: The predicted photospheric emission for an A0 (Vega-like) star as a function of wavelength and distance form the Sun. The photometric sensitivity of SPICA, JWST-MIRI and Herschel PACS are shown for comparison along with example disk excesses. A G2 (Solar type) star at 2 kpc would look like an A0 star at 8 kpc

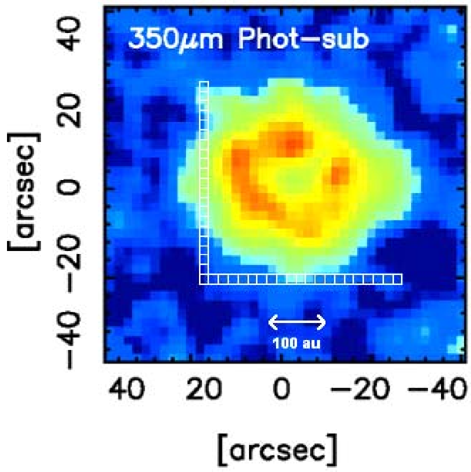


Figure 9: CSO SHARC II 350 μm image of Vega [27] overplotted with the pixel scale of SPICA at 44 to 63 μm (white squares). The spatial resolution is equivalent to ~23 au at this distance allow us to detect the presence of the expected snow-free region of 42 AU in diameter

Water Ice: Water is the first hydrogenated molecule to condense as the temperature decreases and therefore it determines the position of the "snow line" which separates the region of terrestrial, rocky, planet formation from that of the giant planets[23]. Beyond the snow line, in the outer solar system, most of the satellites and small bodies contain a significant fraction of water ice; in the case of comets this fraction is as high as 80%. In the FIR there is a powerful tool for the detection and determination of the amorphous or crystalline state of water ice: namely the transverse optical vibrational bands at 44 μm and ~63 μm[24]. These bands are seen in emission and absorption in young stellar objects[22,25] as well as in Comets within our own Solar system[26]. Indeed the water content of the upper atmospheres of the four gas giants is thought to be highly influenced by cometary impacts such as that of Shoemaker-Levy 9 on Jupiter and it is possible that it is during the later phases of planetary formation that the atmospheres, and indeed the oceans, of the rocky planets are formed from the ices contained in the bombardment of comets and asteroids. In systems such as Vega, Formalhaut and β Pictoris the spatial resolution of SPICA at the 44 μm ice feature will be sufficient to image the distribution of water ice and, through the shape of the feature, whether it is in crystalline of amorphous form (Figure 9) . In the optically thin disks it is not possible to use MIR absorption to trace water ice and the material is too cold to emit in the MIR bands, which anyway are heavily confused with other solid state features. SPICA is the only planned or existing mission that will allow water ice to be observed in all environments and to be able to fully explore its impact on planetary formation and evolution and the emergence of habitable planets.

Exo-planets: Direct imaging of rocky planets within the "habitable zone" around a host star requires a large interferometric mission. However, SPICA can add greatly to the subject due the clean point spread function from the un-segmented high optical quality telescope. This will allow a coronagraph operating from ~3 to 27 μm to directly image and, for the first time, take MIR spectra of young gas giant planets that are within 1 Gyr of formation looking for characteristic features of methane, water and ammonia that are tracers of pre-biotic activity (see Figure 10). The ability of the coronagraph instrument to detect planets close to the host star will be greatly improved by extending the wavelength range to 3.5 μm, as this allows coverage of the predicted 4 μm emission feature[28, 29]. We estimate that with a binary mask type coronagraph we will be able to achieve a contrast of 10^{-6} at an inner working angle of $5\lambda/D_{tel}$ – equivalent to 9 AU (~Saturn's orbit) at 5 μm at 10 parsecs. At this wavelength we probe the younger end of the planet age range giving ~30 target stars within 10 parsecs. Future developments in improving coronagraphic performance should lead to a smaller inner working angle further enhancing the scientific capabilities of SPICA in measuring the MIR spectrum of extra-Solar system planets for the first time.

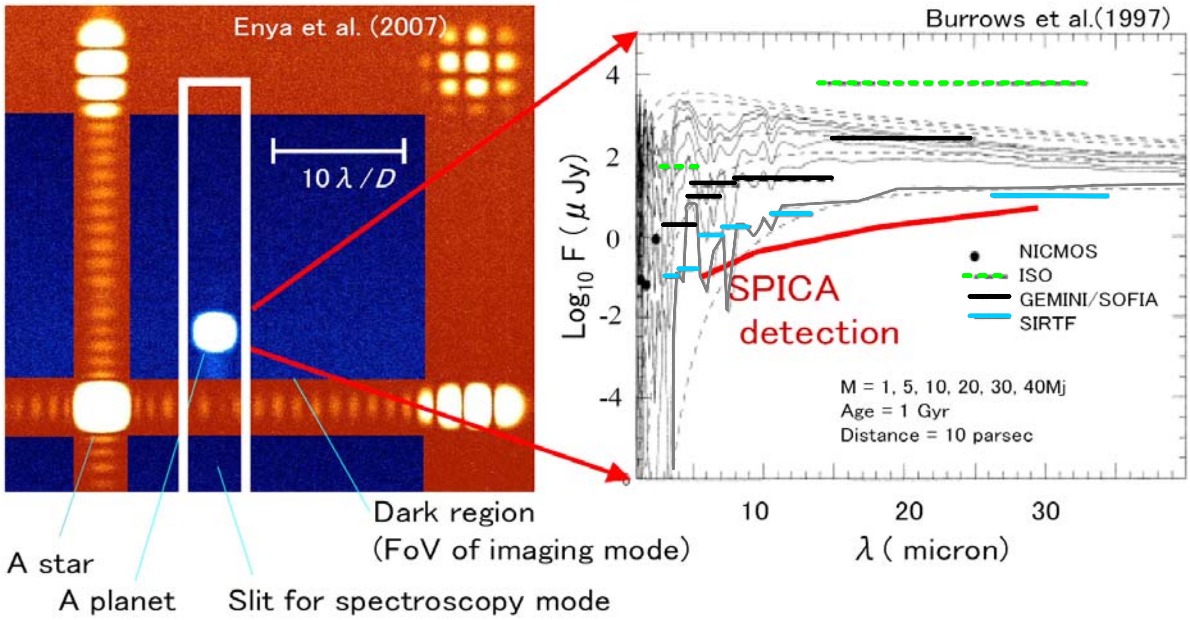


Figure 10 - Composite image showing the operation of the SPICA MIR coronagraph[30] with the spectrograph slit placed over the location of a planet and an example of the typical spectra that it might observe[29]. Here the spectra are shown for various mass planets with Solar composition planet at an age of 1 Gyr at a distance of 10 parsecs - we can see that all these planets will be accessible to coronagraphic studies by SPICA

2.2.1 Dust and Stellar Evolution: from Winds to Protostars and Disks

SPICA will give us an unprecedented window into the key aspects of the dust lifecycle, from the role of stellar winds in the evolution of massive stars to the formation of dust around evolved stars, its processing and evolution in the ISM, dust destruction in supernova-generated shock waves and regions of massive star formation, through to the formation of proto-planetary disks and the dust seen in comets in our own Solar system as discussed in the previous section. The critical keys to unlocking our understanding of the dust evolutionary cycle are MIR/FIR spectroscopy and the FIR to sub-mm dust SED. The former gives direct information on the dust and ice chemical composition and the latter enables us to constrain the dust size distribution. Previous and near future facilities have either insufficient sensitivity, spatial resolution and/or did not have suitable spectrographic capabilities to really address the evolution of dust from its formation, its subsequent processing in the ISM and its re-emergence in dense star forming nebulae. SPICA will have the perfect combination of spatial and spectral resolution combined with high sensitivity to follow the evolution of dust from the creation of sub-micron particles in stellar atmospheres to the formation of planets.

Dust Factories: The principal objects injecting dust into the ambient ISM in our Galaxy are evolved stars; in particular Asymptotic Giant Branch (AGB) stars where complex chemistry occurs in the cool upper atmospheres forming different molecules and mineral species according to the C/O ratio. The upper layers of the stellar atmosphere are driven away from the star by radiation pressure either episodically or by semi-continuous winds, forming dense clumps of material and circumstellar shells (CS). In comparison with mm/submm domains, FIR spectroscopy provides a unique opportunity to probe the inner warm, dense regions of CS around evolved stars. It is in these obscured innermost zones where the most important physical changes within the AGB and planetary nebula (PNe) phases take place such as dust formation, photo-erosion of the CS, origin of mass loss and onset of molecular winds. ISO MIR/FIR observations revealed a rich chemistry in AGB stars and PNe[31] with a plethora of highly excited FIR rotational lines from CO and HCN seen in bright C-rich AGB stars such as IRC+10216[32] together with MIR vibrational bands of non-polar molecules such as C_2H_2. A large number of non-polar organic chemicals (e.g. methane, polyacetylenic chains, pure carbon chains or benzene) play a critical role in the interplay of gas and dust chemistries but they do not possess rotational lines detectable by ground-based radiotelecopes. Only high resolution MIR/FIR vibrational spectroscopy allows access to these missing building blocks of the overall chemistry. The CS shells around AGB stars therefore provide an ideal laboratory for the study of gas chemistry and dust evolution in the transition from circumstellar to interstellar media. This requires a highly sensitive wide band, imaging spectrometer capable of tracing the different species from the inner most parts of the shells out into the interface with the ISM.

The evolution of carbonaceous matter in the ISM: In the ISM, we see atoms, small molecules (light hydrides etc.) and large complex molecules (e.g., PAHs, alcohol, amino acid, etc.), but we do not yet have a good understanding of the processes that take us from one to the other. The role of carbon in this chemical evolution is critical and, whilst most studies of carbonaceous material are presently driven by the observation of the practically ubiquitous aromatic or `PAH' emission bands, SPICA will provide the first opportunity to make extensive observations of the more complex carbonaceous molecules such pure carbon chains, partially or totally hydrogenated carbons and cyano-carbons. The radiative emission and absorption of these molecules can only be detected in the FIR through their vibrational transitions[33] as many of them do not have permanent dipole moments and therefore do not have transitions in the radio or sub-mm. Only an extremely sensitive wide field spectrometer working in the MIR/FIR will have the ability to detect and map the presence of these species.

2.3 Galaxy Evolution, near and far

2.3.1 Background

One of the most important discoveries of recent years has been of a population of massive, dusty star-forming galaxies that emit a significant fraction of their rest-frame bolometric luminosity in the FIR. These ultra-luminous and luminous infrared galaxies ((U)LIRGs) are relatively rare in the local Universe, but are much more common at high-redshift and their integrated luminosity is believed to account for a significant fraction of the Cosmic Infrared Background (CIRB)[34]. The presence of this strongly evolving population of massive, dusty starburst galaxies that form the bulk of their stars at high redshift contradicted early predictions from Cold Dark Matter (CDM)-based, bottom-up hierarchical structure formation models. In CDM models small dark-matter halos form by gravitational collapse; baryonic matter gravitates towards these structures, resulting in the formation of stars and galaxies; small galaxies merge to form massive halos which in turn evolve to form the present-day galaxy population[35]. The challenges to CDM-based semi-analytic galaxy formation model posed by the massive (U)LIRG population are strengthened by evidence that the most rapidly evolving galaxies in the local/intermediate-redshift Universe are relatively smaller structures[36]. This “downsizing” is therefore in exactly the opposite sense to naïve expectations from CDM.

Semi-analytic descriptions of galaxy formation and evolution did not predict the high-redshift starburst population, and accounting for the observed downsizing has driven much recent progress in the models. It has become clear that serious revisions are needed to either the initial mass function in high-redshift star formation[37], and/or the star formation/AGN feedback processes in massive distant star-forming galaxies[38]. Disentangling the interplay between star formation and AGN activity, and their related feeding/feedback mechanisms is crucial to understanding galaxy formation and evolution. The presence of the fingerprints of both AGN and starburst activity in active galaxies and in ULIRGs suggests that black hole formation/mass accretion onto the black hole and star formation are closely linked. Optical studies of local galaxies show that most, if not all, galaxy spheroids host massive relic black-holes which, in turn, suggest that a mass-accreting AGN phase is one through which all galaxies pass. A close correlation is observed between the stellar mass component and central black hole[39] supporting a strong causal link between the growth of the central black hole and the host spheroid.

Reconciling observational data with models raises many unanswered questions:

- What drives the evolution of the massive, dusty distant galaxy population?
- What feedback/interplay exists between the AGN and star-forming phase - is it positive or negative (triggering/quenching star formation) and how does it relate to cosmic downsizing?
- How and when does the ‘normal’, quiescent galaxy population form, and how does it relate to ULIRGs?
- How do galaxy evolution, star formation rate and AGN activity vary with local environment and cosmological epoch?
- How does chemical enrichment of the Universe take place, and what role does it play in galaxy evolution?

It should also be noted that the total energy in the CIRB is larger than that in the cosmic optical background, implying that more than half of the total star-formation activity in the universe is hidden by dust[40]. Recent x-ray observations show that most AGNs are also heavily obscured[41]. Tracing the contributions of these two underlying physical processes to the CIRB is therefore essential to our understanding of how galaxies evolve.

SPICA offers a host of critical MIR/FIR diagnostics with which to address these questions. The unprecedented sensitivity, wavelength coverage and spatial resolution of the SPICA instruments will enable the study of ISM conditions in central starbursts, circumnuclear rings, disks, winds and halos in galactic laboratories in the local Universe, as well as comprehensively in sources in the distant Universe. The field of view of the SPICA instruments provide a considerable spatial multiplexing advantage over other facilities, crucial to studies of both the distant Universe, where source densities and clustering means that multiple sources can be viewed in a single footprint, and mapping of local, resolved, galaxies. Photometrically, SPICA has the sensitivity to detect high-luminosity objects out to z>4 and Milky Way-type populations out to z~1, whilst spectroscopically SPICA will provide a unique means by which to characterise the excitation conditions and source physics of the distant dusty galaxy populations resolved in deep photometric Herschel surveys out to z>3. SPICA will provide the observational means by which to weave together the different galaxian components to form a consistent picture of the spectral and temporal evolution of galaxies. In the remainder of this section we illustrate some of the key science questions that SPICA will enable us to address.

2.3.2 Local galaxies: proxies for the distant Universe

The local universe provides many convenient laboratories in which to study galaxy evolution, the interplay and feedback between energy sources and the chemical evolution of the ISM, over a wide range of environments with different star-formation/AGN activity, metallicity, luminosity, morphology and age. The MIR/FIR plays host to a unique suite of spectroscopic tools (Figure 11) with which to trace the interplay of accretion and star formation throughout different evolutionary phases of galaxies. These diagnostics probe the physical and chemical conditions in different regimes: AGN narrow line regions (NLR), OB star-ionised media, PDRs (photon-dominated regions), XDRs (x-ray dominated regions), as well as molecular structures (e.g. AGN tori) and shocks. The use of such tools to study local galaxies, and on a slightly larger physical scale, galactic halos and the intergalactic medium (IGM), provides critical insight into different phases of cosmic time with much higher spatial resolution and signal-to-noise than is possible in distant sources.

ISO was used to make pioneering spectroscopic studies of small samples of nearby star-forming galaxies and AGNs[42], work that has been recently expanded with Spitzer. Herschel-PACS will provide a further boost, and deliver complete spectra over 57 – 210 μm for a limited number of the brightest local galaxies, and the main PDR tracers in samples of a few hundred galaxies. With its broad instantaneous spectral coverage and resolution of R~1000, SPICA will push past the ISO limitation of low sensitivity and the Herschel limitation of restricted numbers of diagnostic lines. SPICA will give access to the full 5-210μm wavelength range in many different types of AGNs and starbursts including the most enigmatic and obscured infrared galaxies in the local universe[43, 44]: heavily buried starbursts and hidden, 'elusive' AGNs[45, 46]. The latter are the closest analogues to more luminous obscured objects found in large number at high redshift[47]. SPICA will also access the high-J CO rotational[48] and OH emission lines which trace and characterize the warmest/densest molecular gas close to the central AGN, probing the near-AGN environment and importantly testing AGN unification models – the sensitivity of Herschel-PACS will restrict such studies to just the very brightest AGN.

Massive elliptical galaxies are testbeds in which to constrain galaxy evolution models: one cosmology scenario suggests that ellipticals form and evolve rapidly at early epochs leaving them as quiescent objects that evolve passively into old age, whilst other evidence supports the hypothesis that they form as a result of recent galaxy-galaxy merger events and are currently experiencing ongoing star formation. SPICA will provide important clues to the origin and fate of the ISM by quantifying the physical state of the dust and gas in ellipticals, again through the FIR/MIR spectroscopic tool box.

Dwarf galaxies are metal-poor and actively starforming, and so provide an ideal laboratory in which to study the interplay between star formation and the ISM in environments that are reminiscent of conditions likely to be found in very young galaxies in the distant and youthful Universe. Recent observations with ISO and Spitzer have shown that the spectral fingerprints of both dust and gas in local low-metallicity dwarf galaxies (known to be as low as 1/50th solar) differ markedly from those of gas-rich starburst galaxies[49-51]. With a factor of more than 100 improvement in sensitivity in the FIR, SPICA will be able to observe the fine-structure diagnostic lines in dwarf galaxies tracing chemical evolution in regions which approximate to those found in galaxies in the primordial Universe.

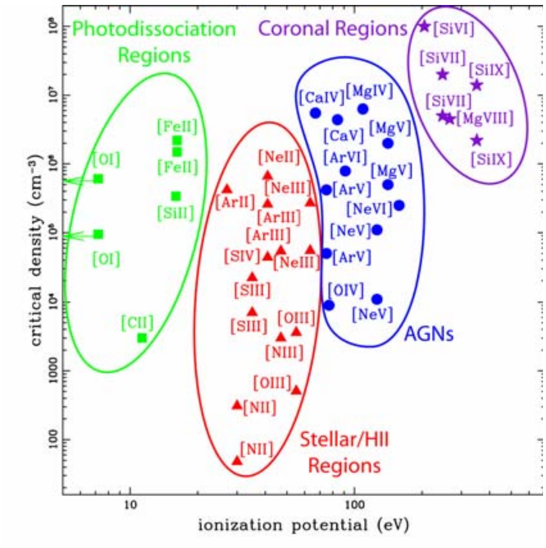


Figure 11 - A selection of the fine-structure atomic and ionic lines that can be observed with SPICA, plotted as a function of critical density and ionization potential. Between them, the lines trace out a wide range of different physical/excitation conditions

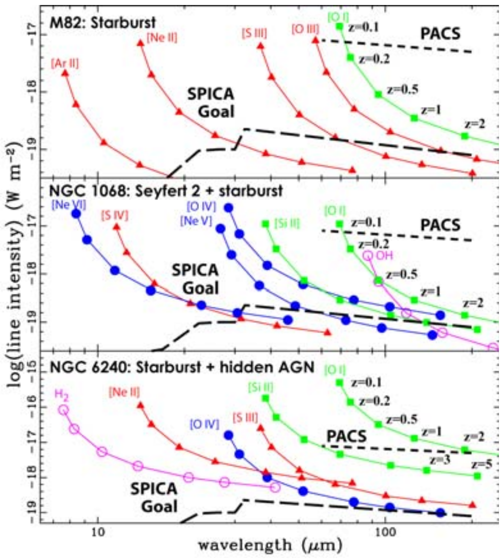


Figure 12 - A plot of intensity vs. redshift of a selection of the key MIR/FIR emission lines visible with SPICA in three archetypical objects: M82 (L_{FIR}~$4x10^{10}L_{\odot}$), NGC1068 (L_{FIR}~$2x10^{11}L_{\odot}$) and NGC6240 (L_{FIR}~$7x10^{11}L_{\odot}$) - in each panel the upper/lower dashed lines denote the 5σ-1hr sensitivity of Herschel-PACS/SPICA respectively.

Detecting and establishing a comprehensive inventory of the matter reservoir in galaxies provides important insight into how the mass density in the Universe is distributed. Molecular hydrogen is the most abundant molecule in the Universe, and plays a fundamental role in many different astronomical contexts. While the NIR ro-vibrational lines of H_2 near 2μm trace a hot gas component (~2000 K), this comprises only a small fraction of H_2 in galaxies. In contrast, the four MIR ground-state rotational transitions (9.6, 12.3, 17 and 28.2 μm) trace a ubiquitous and more abundant warm phase (~100 to 200 K). Observations with ISO and Spitzer covered all four transitions and showed that at least 30% of the total gas mass in ULIRGs, AGNs and starburst galaxies[52, 53] and perhaps more in disk galaxies[54, 55] resides in a warm, molecular H_2 component, with much of this undetected through the usual proxy, CO. Through the combination of observations of the MIR lines with SPICA (at R~30000) and ground based telescopes, it will be possible to routinely detect molecular H_2, mapping the distribution of the extended halo component in local galaxies, thus enabling a census of molecular hydrogen in the local galaxy population. Such detailed observations will shed new light on the origin of the molecular H_2 emission in galaxies (PDRs, shocked gas, x-ray heating) and assess the importance of large-scale intergalactic shocks induced by galaxy collisions as evidenced by recent Spitzer results. SPICA will open a new window on structure formation in the universe by determining the incidence of this phenomenon in the local universe and by providing the first measurements of these lines in distant merging and colliding galaxies, which were much more prevalent at early epochs.

Observations of the Lyman alpha forest provide conclusive evidence for the presence of metals at z~3 in very low column density material[56] N(HI)< $10^{15}cm^{-2}$. It is unknown how much of the chemical enrichment of the IGM is from primordial galaxies and how much is due to galaxies at later epochs. By studying material ejected from galaxies, we can investigate the origin of the IGM and hence of chemical enrichment. Several explanations have been put forward to explain the origin of enrichment, including supernovae-driven transport of metal-enriched gas from primordial galaxies[57], and radiation- pressure (AGN-driven)[58] or cosmic-ray driven superwinds[59]. SPICA will have the spectroscopic sensitivity to probe the ionisation mechanism of this cool ISM phase, with velocity information key to measuring the rate of injection of ISM material into the intra-cluster/IGM, and thus to measuring how much of the 'entropy floor' in clusters and galaxy groups is a result of 'preheating' of the ISM as it is released into the IGM. SPICA will also map the morphology of the material around galaxies, so tracing the formation of disk galaxies and uniting theories of disk/halo interaction out to the halo/IGM interface. Fine structure lines as well as rotational lines of molecular hydrogen will trace any cool "unseen" gas component in the outermost regions of galaxies where the N(HI) of the diffuse atomic component can be as low as $10^{20}cm^{-2}$.

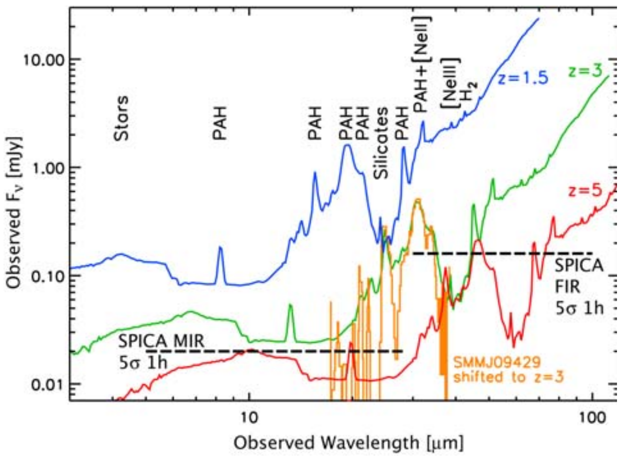


Figure 13 - Shown in black is a local ULIRG template that has been fit to the observed spectrum SMM J09429 (red)[62] (note that both spectra have been redshifted to z~3 for illustrative purposes). SPICA will have the sensitivity in low-resolution mode (R~100) to detect PAH/silicate features in dusty distant galaxies out to z~3 in 1 hour's integration, and out to z>4 in 10 hours. These features provide important pointers to the z>physical processes powering distant dusty galaxies, but also contaminate deep photometric MIR surveys.

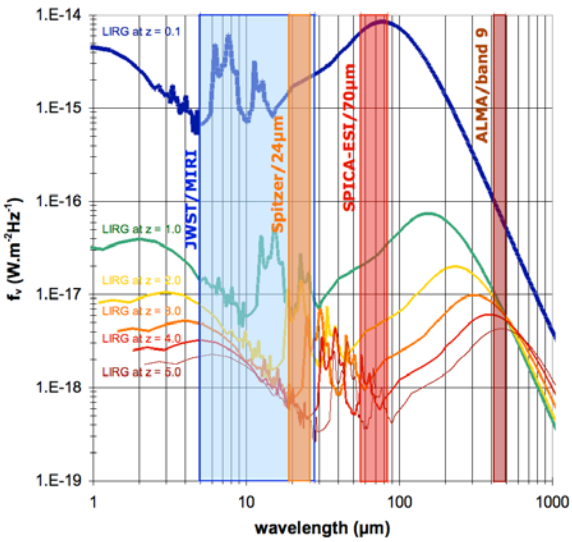


Figure 14 - A plot of the spectral coverage of a selection of photometric surveys/telescopes, overlaid on the redshifted SED of the LIRG model of Lagache et. al. [74]. The 70 μm SPICA waveband remains free of contamination from redshifted PAH/silicate features to out to z~3; in contrast features move into JWST/MIRI 5-28 μm band at z<1.

Whilst the luminosity and type of a galaxy have a strong influence on its evolutionary path, its local environment undoubtedly also has an effect. SPICA spectroscopy provides a sensitive means by which to investigate the interplay between nature/nuture: understanding the interrelationship and feedback between disks of galaxies, halos and the intracluster medium offers a means of tracing diffuse gas structures which must link galaxies to the Cosmic Web.

2.3.3 The AGN-starburst connection at high-redshift

By the launch of SPICA, deep cosmological surveys will have detected many thousands of faint and distant MIR/FIR galaxies, ranging from sources that dominate the source counts, to those much rarer and more exotic at the highest redshifts. Observational evidence suggests that the properties of the faint MIR/FIR population differ markedly from those of similarly luminous, local infrared galaxies[60]. Herschel will be able to measure the FIR continuum and so constrain the dust temperature and mass of the massive, high-redshift population out to z~2. SPICA will go beyond this, and through spectroscopy will constrain many of the key physical properties of the gas such as temperature, density and metallicity, as well as characterising the radiation field so distinguishing the AGN and starburst characteristics of these sources. Figure 12 shows the predicted intensities of a selection of fine-structure emission lines that trace AGN, stellar ionization and PDR regimes, plotted as a function of redshift for three template local objects -- M82, NGC1068 and NGC6240. Sensitivity is key to our ability to probe the distant Universe. With SOAP detectors (5σ-1hr few x 10^{-18}Wm^{-2}) it will be possible to detect the very brightest lines in the most exotic objects at high-z; in contrast, with goal sensitivity (5σ-1hr few x 10^{-19}Wm^{-2}), not only the brightest MIR line emission (e.g. [NeII]) will be visible from a significant fraction of the SCUBA and Spitzer populations ($L_{IR}>10^{11}$ $L_\odot$) but also the fainter, but diagnostically important lines of, e.g. [OIV], [NeV] and the ground-state rotational transitions of H_2. SPICA will provide an important complement to ALMA which will trace the colder, molecular component of the ISM through observations of redshifted CO, HCN as well as [CI] and the longer-wavelength rest-frame FIR cooling lines as they are redshifted into the submm waveband.

Simulations suggest that an evolutionary link exists between luminous high-redshift starbursts and obscured/unobscured QSOs with feedback playing an important role[35,37,67]. Models are strongly parameter-dependent, however, and are in great need of observational constraints. MIR emission is largely unabsorbed by dust and so can be detected from even the most highly-obscured Compton-thick AGN. Spectroscopic[63, 64] and photometric[65, 66] evidence from Spitzer suggest that significant populations of high-z obscured AGN are not well-represented in traditional x-ray and optical surveys. Fine-structure emission lines can be combined with the diagnostic templates of PAH features and silicates (Figure 13) developed from ISO and Spitzer observations, to distinguish between starbursts, the warm MIR continua of un-obscured AGN and the heavily obscured continua

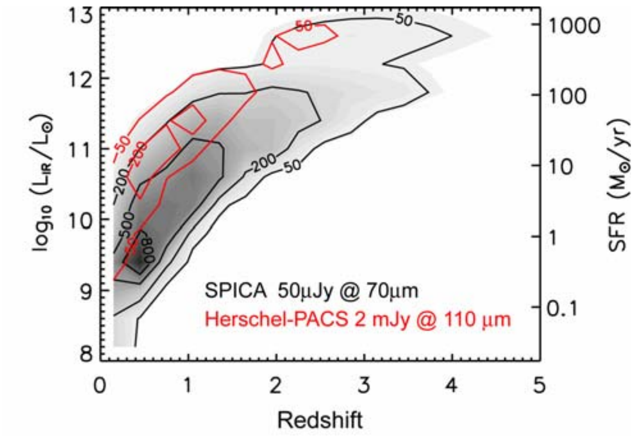


Figure 15 - Expected number of sources of a given LIR (or equivalently star formation rate) and redshift that will be detected in a 70 µm confusion-limited (~50 µJy) survey of 1000 sq. arcmins with SPICA (greyscale/black contours) with PACS (to 2 mJy at 110 µm, red contours). Contours indicate the number of sources per (Log L_{IR}, z) bin of (0.4, 0.3). PACS will be able to detect only the most luminous objects at a given redshift. JWST 24 µm surveys to 5 µJy (not shown) will detect sources comparable in number and L_{IR}/z distribution to SPICA, however with considerable uncertainty in the L_{IR} derived from 24 µm fluxes due to contamination from PAH emission.

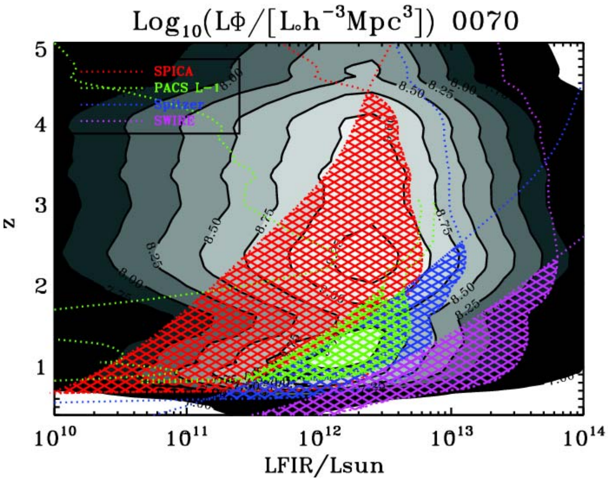


Figure 16 - A plot of the FIR Luminosity density (i.e. luminosity-weighted luminosity function) as a function of FIR luminos ity and redshift (greyscale and contours). This illustrates the galaxies and epochs that contribute most to the star-formation history of the Universe (in the model of Lagache et al.[74]). The ability of 70 µm surveys to probe this function is indicated by colour hatching: SPICA (1000sq. arcmin 50 µJy red); Spitzer (Deep surveys -- Blue and SWIRE--Magenta). Herschel GT surveys cannot constrain this function at 70 µm, while the power of the 110 µm surveys are shown (green). Herschel and Spitzer sample the z~1 peak: only SPICA can probe the z~2.5 peak.

of some AGN. Using SPICA we will therefore start to trace the evolutionary sequence and state of luminous infrared galaxies out to z~4 and beyond.

The observed similarities between MIR spectra of LIRGS at the present epoch out to z~2.5 suggest similarities in dust properties, and thus that significant enrichment and evolution has already taken place by z~2.5[67, 68]. The question that arises from this is; when did the bulk of dust production and evolution take place? In young galaxies, delayed injection of heavy elements from AGB stars would, for example, weaken PAH emission[69], and increase the relative importance of other sources of dust such as supernovae or AGN winds dust[70]. Such changes, and thus the evolution of the rest-frame MIR, will be detectable with SPICA.

Observations of intermediate and high-redshift sources have shown that the co-moving star formation rate density in the Universe was at least a factor of 10 higher at a redshift of unity[71,72], with more than half of the stars in the universe formed since z~1. Previous generations of spectrometer have only had the sensitivity to detect starbursts such as M82 and brighter at intermediate/high redshift, however such objects make up a small fraction of galaxies. With SPICA, for the first time we will be able to characterise the ISM of the complete z~1 population, and so follow the evolution as a function of redshift of these ubiquitous galaxies. Galaxies such as our own Milky Way will be easily detectable in the continuum out to z~1, whilst the MIR/FIR cooling lines will be visible out to z~0.5 where the universal SFR has increased by close to an order of magnitude. Thus, we will be able to start to determine whether present-day galaxies grew by collisions/merging of smaller objects as suggested by CDM cosmology, or whether massive galaxies with higher SFR were already in place by z~1.

2.3.4 Deep cosmological surveys

Deep continuum surveys at 70 µm: A comparison between the integrated cosmic optical background and the cosmic infrared background shows that around 50% of photons produced by stellar nucleosynthesis and massive, accretion-driven black hole growth over the lifetime of the Universe have been absorbed by dust and re-emitted in the FIR. Understanding how and when these FIR photons were emitted is therefore central to understanding galaxy formation. Both ground-based sub-millimetre (submm) surveys with existing facilities (SCUBA, MAMBO, LABOCA, SCUBA2) and FIR surveys from space (ISO, Spitzer) are limited by the confusion that results from modest angular resolution, and are sensitive only to the most luminous and distant galaxies, or very nearby ones. Such galaxies contribute less than half of the background at these wavelengths, and make up an even smaller fraction of the integrated CIRB. Herschel-SPIRE and PACS will open new windows in the FIR above 100 μm, however our current knowledge of source densities at these wavelengths suggest that we will resolve only 50% of the CIRB because of confusion. Confusion dominates the performance of a 3.5-m telescope long-ward of 70 μm; short-ward of ~70 μm the sensitivity of Herschel-PACS detectors is the limiting factor.

ALMA (operating in continuum mode) will probe the submm regime with higher angular resolution, however contributions to the CIRB determined from submm fluxes will have systematic uncertainties because of the extrapolation required to go from the submm to the ~140-μm peak of the CIRB. Contributions to the CIRB determined from deep JWST surveys at 24 μm, also at higher angular resolution, will also have uncertainties, this time originating from contamination from the redshifted PAH/silicate features (Figure 14). Thus, the origin of CIRB and its implications on galaxy formation will remain an open question to both existing and planned generations of instrumentation.

The 70 μm confusion limit for SPICA is ~50 μJy, a depth that can be achieved with goal detector sensitivity in a few minutes with simultaneous measurements of similar sensitivity in the other two wavebands of the SPICA FIR instrument. Using current assumptions of the intensity of the CIRB at this wavelength, a 70 μm confusion-limited survey (Figures 15, 16) would resolve more than 90% of the CIRB over 80% of the Hubble time (z~2), by detecting galaxies down to the star formation rate (SFR) regime where the UV meets the IR, i.e. around 10 M_{sol}/yr [74]. SPICA will also be sensitive to many galaxies as quiescent as our own ($L_{IR} < 10^{10} L_{sol}$) out to z~1 (Figures 15, 16), where the cosmic SFR peaks. A 70μm confusion-limited survey will not only provide the best measurement of the SFR in distant galaxies, without being affected by e.g. PAHs, but it will also complete the census on the growth of massive black holes by probing the missing population of dust-obscured, mostly Compton-thick, AGNs responsible for the unresolved peak of the X-ray background at 30 keV. These AGNs are missed by the deepest X-ray surveys (the prototype Compton-thick AGN NGC 1068 would be missed above z=0.5 even in 2 Ms with Chandra), yet reveal themselves in the MIR (as expected from their high level of obscuration) through stacking analyses at both MIR and x-ray wavelengths. Spitzer MIR observations have provided a tantalising photometric glimpse into this population[75]. SPICA will take the next step and confirm and interrogate the AGN nature of sources using the MIR diagnostic lines characteristic of the hard photon fields found in AGNs.

Deep MIR surveys - Stellar mass assembly of galaxies: Observations both from the ground and space have been used extensively to study the evolution of mass distribution of galaxies with redshift. Large populations of distant massive ULIRGs have been identified in the shallow, large-area SWIRE survey using colour-colour selection techniques based around the broad, rest-frame near-IR SED peak [77]. These sources have very similar properties to high-redshift, submm-selected galaxies, and are likely precursors of present-day ellipticals. With SPICA it will be possible to extend such studies to lower luminosities, smaller stellar masses and larger redshifts. The peak of the rest-frame, near-IR stellar emission in high-z galaxies will be redshifted into the MIR (Figure 13, 14). SPICA will have the photometric sensitivity to detect stellar masses of $10^9 M_\odot$, out to z~10 and more modest mass assemblies of $10^8 M_\odot$ out to z ~0.5, whilst at z ~ 5, SPICA will detect Lyman Break Galaxies of the type recently found in the CDF-S[78] which have lower stellar masses (~$10^9 M_\odot$) than their z ~ 3 counterparts.

Both JWST MIRI and SPICA MIR will provide unprecedented angular resolution at MIR wavelengths, ~ 0.35 arcsec at the shortest wavelengths, comparable to the angular resolution of HST/NICMOS in the near-IR. At this angular resolution it will be possible to study the morphology of both stellar emission in galaxies out to high z, as is now possible at shorter wavelengths with ultra-deep HST/NICMOS observations. Whilst deep-MIR extragalactic surveys will be performed by JWST MIRI prior to the launch of SPICA with slightly better sensitivity at the short wavelengths (Figure 1), with its much larger field of view, and multi-waveband observation capability over four MIR channels (5 to 38 μm), SPICA will not only map the sky more rapidly at >~ 15 um (and at comparable speeds at shorter wavelengths; see Figure 18), but also trace both the stellar (short MIR) and dust components (long MIR) in the same field.

Punching through the traditional FIR confusion limit: To resolve the objects making up the CIRB requires the spatial resolution of an interferometer such as FIRI, however, SPICA's combination of spectral imaging and large wavelength coverage provides a novel way to break the traditional confusion limit by adding wavelength as a third dimension to deep, cosmological surveys. Sources can be identified by emission from redshifted MIR/FIR cooling lines produced by star formation and AGN activity, rather than by the broad-band signatures of warm dust. Redshifts accurate enough for immediate follow-up ground-based CO observations (tracing the molecular

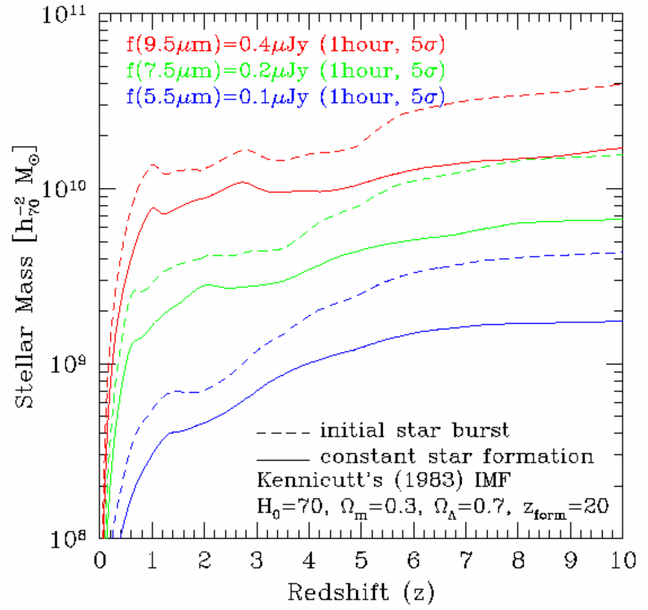


Figure 17 - A plot illustrating the sensitivity of SPICA MIR to stellar mass as a function of redshift at a selection of different wavelengths. SPICA will have the photometric sensitivity to detect stellar masses of $10^9 M_\odot$, out to z~10, Lyman Break Galaxies with stellar masses ~ 10^9 $M_\odot$ out to z~5, and more modest masses of 10^8 $M_\odot$ out to z~0.5

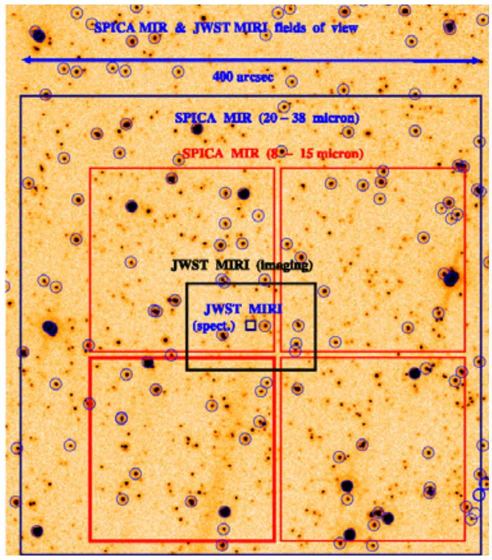


Figure 18 - The FOV of 2 of the 4 channels of the SPICA MIR (for further technical details see Figure 22 in §4.4) are shown overlaid on the GOODS-S (epoch 2) IRAC 8 μm image. Ringed objects marked have fluxes of S(8 μm)>20μJy, the 5σ-1hr sensitivity limit for detection in SPICA MIR low-resolution spectroscopy. Shown for comparison are JWST FOVs: more than 100 sources can be observed in a single pointing of SPICA-MIR, in contrast to ~few with the JWST.

gas component) can be determined from the detected lines, while line ratios provide a first indication of the nature of the source powering the FIR emission. In simulations of deep, blind spectral line surveys (rms noise level of 0.4mJy 100hrs SOAP/10hrs GOAL at R~1000) with SPICA FIR[79] it was possible to detect and determine redshifts of sources brighter than 1 mJy at 120 μm out to z~2.5 using the 5 strongest FIR cooling lines (including [OI] at 63 μm), thus probing to a factor of 5 below the 120 μm continuum confusion limit. Sources at even higher redshift can be recovered by including MIR emission lines. Simulations suggest that sufficient sources/redshifts can be detected to differentiate between galaxy evolution models, and thus place tight constraints on the origin and history of our own and other galaxies, by observing areas as small as 4' x 4'.

Cosmology using low-resolution spectroscopy: The rich spectrum of PAH and silicate features found in the MIR of both local[80] and distant galaxies[81] provide an excellent means through which to undertake deep, blind surveys using low-resolution spectroscopy. In the deepest spectra obtained with Spitzer IRS[82], these features can be seen out to z>2 in sources that are both optically and MIR-faint (S(24 μm)~ 100 μJy) – low-medium resolution spectroscopy (R~100-200) thus provides an excellent means by which to determine source redshifts and measure the physical conditions in sources that would not be detectable using optical or near-IR spectrographs on even the largest ground-based telescopes. The low-resolution modes of the SPICA MIR and FIR instruments will enable large-scale spectroscopic surveys of very faint galaxies, down to ~ 20 μJy and ~100 μJy, respectively. The source density of IR galaxies at these flux levels is known from deep Spitzer MIPS surveys[83], and one would expect to detect ~10 sources with S(24 μm)> 100 μJy in the 2' x 2' FOV of SPICA FIR, with much larger numbers in the slitless, grism-based MIR modules. A wide-field, low-resolution spectroscopic surveys with SPICA FIR over an area of the size of the COSMOS field (2 square degrees) with integration time of 1 hour per pointing would provide spectra of ~ 18000 high-z galaxies in 1800 hours, more than a factor of 50 more than the total number of high-z galaxies observed with Spitzer IRS, and a significant increase on those observed by JWST by the launch date of SPICA. Through measurements of the PAH features we will not only be able to directly estimate star formation rates[84], but also to measure redshifts and so start to evaluate the co-moving space density of this dusty population and to constrain the bolometric luminosity function of luminous infrared galaxies.

2.4 Discovery Science

The science case we have presented in this section illustrates the concrete and definitive progress in our understanding of the Universe that SPICA will allow. However, as with all strides in increased sensitivity or the opening of new wavelength bands, new discoveries are certain once SPICA starts observing. Witness the discoveries made by IRAS, ISO and Spitzer of ULIRGS, crystalline silicates in dust in astrophysical sources and the presence of large amounts of dust in high redshift galaxies. With an increase in sensitivity of another two orders of magnitude in the FIR we can expect some real progress in areas where even upper limits will constrain the boundaries of what are, today, rather speculative theories, to wit:

- Constraints on the emission of ground state H_2 emission from the first (population III) generation of stars
- The detection of biomarkers in the MIR spectra of exo-planets and/or the primordial material in proto-planetary disks
- The detection of H_2 haloes around galaxies in the local Universe
- With sufficient technical development of coronagraphic techniques: the imaging of any planets in the habitable zone in the nearest few stars
- The detection of the far infrared transitions of PAHs in the interstellar medium. The very large molecules thought to comprise the PAHs, and which give rise to the characteristic features in the NIR, have vibrational transitions in the FIR which are widespread and extremely weak[85].
- The direct detection of dust formation in super novae in external galaxies and the determination of the origin of the large amounts of dust in high redshift galaxies

2.5 SPICA Science Requirements

Table 1 summarises the key functional and performance requirements of SPICA that are necessary to achieve the scientific programme described above.

Requirement	Comment
Spacecraft	3-axis stabilized with high pointing accuracy and stability in a thermally benign orbit which provides all sky access during the course of the mission
Telescope	As large a monolithic aperture possible compatible with the launcher fairing (3.5 m). Diffraction limited imaging at 5μm over a field of view sufficiently large to accommodate the proposed focal plane instruments. Point spread function sufficiently controlled to allow pupil mask coronagraphy in the MIR. Temperature < 5 K to remove self emission in the FIR. Stray-light controlled to a level to allow Zodiacal light limited sensitivity.
Focal plane instruments	Full wavelength coverage from 5 to 210 μm. Instruments required to provide Photometric camera function, a spectroscopic function and a coronagraph working in the MIR range. The instrument instantaneous field of view in both Photometer and Spectrometer modes to be as large as possible dictated by available spacecraft resources and technology. Spectral resolution vs. wavelength as defined in Figure 19. Sensitivity as close to background limited as possible.
Operations	Sufficient telemetry resources to allow uncompressed science data downlink (~30Gbytes/day) however a strong design driver exists for higher total capacities to allow downlink of raw detector samples.

Table 1 – Summary of the key functional and performance requirements of SPICA

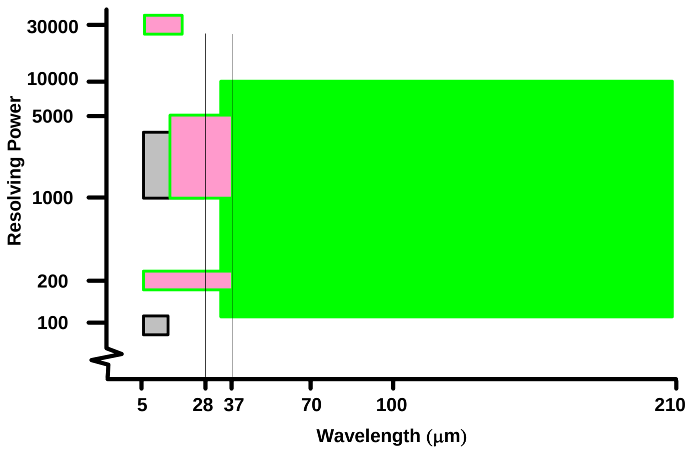


Figure 19 – Required spectroscopic capabilities of the SPICA focal plane instruments expressed as spectral resolving power versus wavelength. The grey boxes show the JWST-MIRI resolving power versus wavelength, pink boxes the proposed SPICA-MIR capability and the green box the SPICA-FIR capability. The vertical lines at ~28 and ~37 μm show the long wavelength edges of Si:As and Si:Sb photoconductors coverage respectively. Note how we plan to complement the JWST capabilities by providing broader wavelength coverage and higher spectral resolution where SPICA and JWST overlap.

3. SPICA Mission Profile

Overview: SPICA is part of the JAXA future science programme and is planned for launch in 2017. The mission follows on both scientifically and technically from the highly successful AKARI mission. High photometric sensitivity observations in the MIR/FIR are made possible thanks to the large 3.5m telescope which is actively cooled to below 5 K to effectively eliminate the non-astronomical photon noise. High spatial resolution is achieved thanks to the large aperture, monolithic primary mirror and the appropriate tolerances on the telescope and mirror surfaces to achieve diffraction limited performance at 5 μm.

Launch/Orbit: The launcher selected for SPICA is the JAXA H2A-202, which is compatible with the overall mission requirements. It launches from the Tanegashima Space Centre and can deliver a payload mass 2600kg to L2. The H2A-202 is the smallest variant of the H2A and therefore any growth in the payload mass can be accommodated by selecting a larger variant. The payload fairing on the launcher is ø4600 mm which is compatible with the 3.5 m telescope and associated thermal baffling. The orbit selected for SPICA is the S-E L2 libration point as it provides a benign and stable thermal environment required to cool the payload to < 5 K as well as a good instantaneous sky visibility.

Space segment: In order to meet the 2017 launch date and keep within the financial constraints of the participating agencies, the key elements of the space segment must rely either on existing technology or on modest development programmes. A nominal lifetime of five years is baselined, permitting the science objectives to be met while allowing margin for exploratory science. Sufficient spacecraft consumables for attitude control etc. will be carried to permit ten years of operations in order to accommodate possible mission extensions.

Ground segment: The mission requires a minimum of five hours ground contact per day. The spacecraft and instruments will have sufficient autonomy functions to be tolerant to the loss of ground contact for extended periods of time. The mission will be greatly enhanced by the provision of additional ground contact time to increase the telemetry budget.

Critical Issues

Spacecraft Thermal design: This is the main critical technical issue facing the spacecraft. The main components of this challenge include: (1) the speed and efficiency of the cool down from ambient temperature at launch to the operational cryogenic temperatures and (2) the steady state temperatures and cooler heat loads during nominal operations. Regarding the cool down; the design must account for the actual heat lift capacities of the coolers at different operating temperatures and avoid any pinch points where static heat loads exceed the system cooling capacity. The scientific impact of a non-compliant thermal system will depend on the exact nature of the problem and ranges from degraded performance to loss of function. The thermal design of SPICA has been the subject of much detailed design and analysis[89] and is recognised within the SPICA project as requiring ongoing detailed analysis and verification to ensure that the requirements are met.

AIT: System-level test and calibration represents a significant challenge in the SPICA programme. The satellite will be launched warm, followed by a controlled cool down to the operating temperature during the initial phases of the mission. This approach brings several benefits, in particular making the spacecraft simpler and lighter. It does, however make it more difficult to simulate a flight-like environment for the spacecraft and payload. One particular challenge is verification of the various payload opto-mechanical budgets under a flight-like thermal and zero-g environment. To address this, an existing JAXA cryogenic test facility is to be upgraded to allow optical testing of the telescope assembly and instrument suite at the operating temperature of < 5 K. Other aspects of the AIT programme are considered to be of a more routine nature.

4. SPICA payload

4.1 SPICA Payload Overview

Four components of the SPICA payload are described in this section, (1) the SPICA Telescope Assembly (STA), (2) the MIR Coronagraph, (3) the MIR imaging spectrometer and (4) the FIR imaging spectrometer (ESI). These items satisfy the mission requirement outlined in Table 2. The division of the functions of the different focal plane instruments (See Table 1) is largely dictated by the available detector technologies, which in turn define the types of instrument design that are most appropriate.

Indicative overall resources/interfaces for the instrument suite are summarised in Table 2.

Parameter	Baseline Requirement/specification	Comments
Instrument suite mass	< 200 kg total: 100 kg in Focal plane 100 kg within Service Module	This is the overall mass of the instruments including the warm electronics. It is subject to revision during the SPICA Phase-A study.
Cryogenic focal plane accommodation	ø2500mm x 500mm height	The telescope primary focus is at the centre of this volume.
Instrument thermal interfaces	5mW @ 1.7K 10mW @ 2.5K 15mW @ 4.5K	These values are based on EOL performance of the spacecraft coolers
Power for instrument analogue and digital electronics	200W	This is the unregulated power budget for all the instruments.
Telemetry budget	60GB daily TM	This corresponds to ~6MBits/s averaged over a 24 hour period and includes the capacity provided by Cebreros which is a part of this proposal
Spacecraft Pointing	Absolute/reconstructed: 1” Stability: 0.03” rms over 60 seconds	The absolute pointing requirements are met after in-orbit calibration of the AOCS

Table 2 – SPICA instrument interface and resource summary

4.2 Instrument procurement and development

The SPICA instruments are PI led and will be developed by consortia of researchers mainly from non-commercial research institutes and universities. In this context, the importance of developing the instruments within the framework of a rigorous set of requirement and design reviews is acknowledged. This is especially true for the assessment and definition study phases of the various SPICA instruments. Independent reviews will be carried out on each of the instruments to the same standard as that expected of European Industry when delivering to ESA.

4.3 FIR Imaging Spectrometer – ESI (European SPICA Instrument)

4.3.1 Description and Key Characteristics

The baseline optical configuration of ESI is a Mach-Zehnder imaging Fourier Transform Spectrometer. The principal advantages of this type of spectrometer for ESI are the high mapping speed of the FTS due to spatial multiplexing, the ability to incorporate straightforwardly a photometric imaging mode and the operational flexibility to tailor the spectral resolution to the science programme. A grating spectrometer layout has been studied, but due to the limited field of view for the available number of pixels and the difficulty of incorporating a wide field photometer mode, this layout has not been pursued at this time. The principal performance characteristics of ESI, together with comments on scientific performance are outlined in Table 3.

Parameter	Specification	Comments / tradeoffs
Instrument type	Imaging Fourier Transform Spectrometer	Allows for a broad-band photometry imaging mode as well as variable resolution imaging spectrometry
Wavelength range	30-210μm: Nominally divided into ~ 3-4 sub-bands.	Short wavelength limit defined by overlap with MIR instrument; long wavelength limit defined by the [NII] 206μm line. Division of the spectral range into the different bands depends on the final detector technology selection.
Instantaneous Field of View	2’x2’	Derived from a science requirement to image diffuse emissions and give a large spatial multiplexing advantage
Angular resolution	Diffraction limited performance above 40μm	Places constraints on ESI optics. The telescope is specified to be diffraction limited at 5 μm.
Pixel spacing	Fλ/2 at the centre of each band	Critical image sampling

Parameter	Specification	Comments / tradeoffs
Spectral resolution	Photometric Imaging: R <10 Low Resolution Mode: R ~ 100 Med. Resolution Mode: R ~ 2000 @ 100μm High Resolution Mode: R ~ 10000 (goal 100μm)	To achieve the stated medium resolution requirement the required optical path difference is 140mm. It is expected that the goal resolution of 10 000 will be met within a restricted field of view
Sensitivity	Broad band photometry < 50μJy (5σ-1 hour) Medium resolution line sensitivity: < 10 x10^{-20} W/m^2	Required detector NEP ~1x10^{-19} W/√Hz.
Dynamic range	> 1000 within a single field of view	A supplementary requirement exists to not saturate the detectors in high spectral resolution on a bright source

Table 3 – Key scientific performance characteristics of ESI

A possible optical layout of the instrument is shown in Figure 20. This layout incorporates a double fold mirror within the spectrometer mechanism which yields a folding factor of eight. An internal pupil diameter of ~30 mm and a mirror scan range of ~85mm will achieve the goal spectral resolution of $R = \sigma/\Delta\sigma = 10\ 000$ based on $\Delta\sigma = 1.2/2\text{xOPD}$ in the centre of the ESI band.

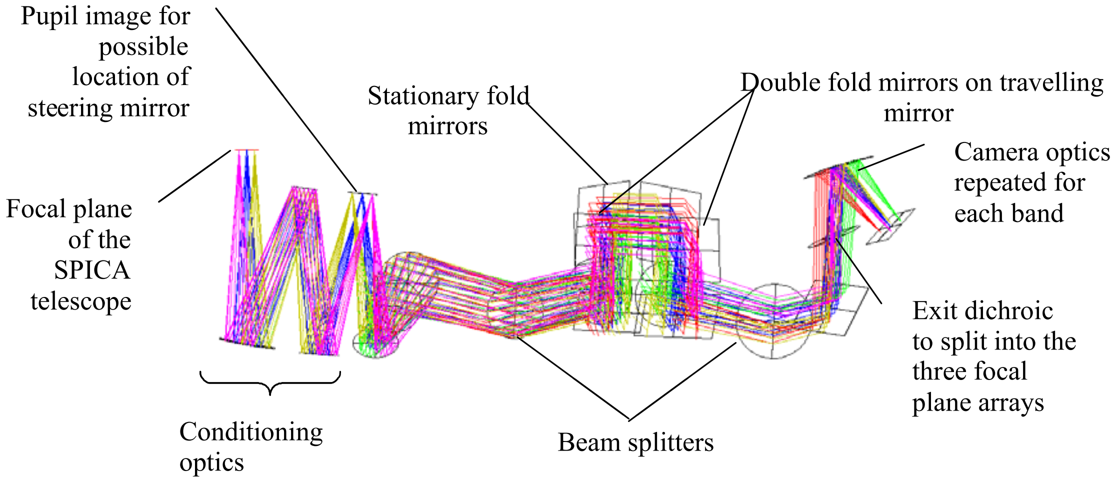


Figure 20 – Possible ESI optical layout. Note: only one arm of the Mach-Zehnder FTS shown for clarity.

4.3.2 *Performance with respect to science objectives*

Detector technology for ESI has been a critical focus of the instrument studies over the past 2-3 years. The final baselining of the detector technology for ESI is to be made in the autumn of 2009 following a targeted programme of technology development. The delay in making the final selection of the technology is a calculated approach to maximising the scientific return of the instrument while grounding the final selection within the real-world constraints of technology readiness, spacecraft resources and interfaces, system reliability as well as schedule and budgetary considerations. A summary of detector performance together with a list of architectural design features and operational constraints/considerations is shown in Table 4

.

	Option-A TES Bolometer	Option-B Photoconductor
Description	• Band A: 30-57μm: • Band B: 57-106 μm • Band C: 106-210 μm	• Band A: 27-37μm: monolithic Si:Sb BIB array • Band B: 45-110μm: unstressed monolithic Ge:Ga • Band C: 110-210μm: array: Stressed Ge:Ga
NEP	~ 1 x 10^{-19} W/√Hz	a few x 10^{-18} W/√Hz
Pixel (array) size	Pixel Pitch ~ 2.5mm • Band A: 64x64 Px => 160 x 160 mm • Band B : 38x38 Px => 95 x 95 mm • Band C: 20x20Px => 50 x 50 mm	• Band A: 256x256 Px => 12.8 x 12.8 mm • Band B: 32x32 Px => 115 x 115 mm • Band C: 32x32 Px => 115 x 115 mm
Readout	Frequency Division multiplexed. Series SQUID array cold amplification	Direct Injection (DI) circuit cold readout of photoelectric current.
Wavelength Coverage	30-210 μm	30-37μm + 45-206μm Poor performance over "missing octave"
Dynamic range	Fundamentally linked to NEP and limited to ~ 10000 @ 1x10^{-19}W/√Hz	Adjustable via switchable integrating capacitor and setting of the integration period.

	Option-A TES Bolometer	Option-B Photoconductor
Linearity	Good linearity with feedback to the readout SQUIDs	Ge:Ga detectors have multiple time constants which gives rise to frequency dependant detector response which needs sophisticated characterization and calibration
Cosmic ray susceptibility	Absorber has low cross section and detector recovers in several τ_c	Relatively high cross-sectional area gives rise to high hit rate. Hits change responsivity but calibration restored with curing techniques.
Time constant	~ 10 ms	~ 10 ms for DI
Base Operating Temperature	100-mK for detector elements	1.7–4.5K for detector elements.
Heritage summary (see also text)	X-ray TES arrays and are under extensive development by SRON for XEUS and JAXA for NEXT and have been deployed in SCUBA-2. ISAS is developing TES detectors for x-Ray application. IR TES detectors used on the GBT and SCUBA-2	ESI detectors would be an evolution of the Herschel/PACS and SPITZER MIPS detectors. AKARI FIS uses Ge:Ga stressed and unstressed detectors.
TRL	4	5-6

Table 4 – ESI Detector options

TES Bolometers: TES bolometers require a base temperature in the order of 50-70mK to achieve the required NEP. This adds significantly to the complexity and mass of the instrument as it necessitates an instrument provided sub-K cooler. The justifications for retaining the design option of TES bolometers detectors with this extra level of complexity are that (1) there are very good prospects for achieving the ESI detector goal NEP within the schedule constraints of SPICA with TES detectors, (2) the spectral response of the TES gives good access to the wavelength band around 40μm where photoconductors perform poorly, (3) the effects of cosmic ray hits and non-linear response are more benign for bolometers compared with photoconductors. A key disadvantage of bolometer detectors compared with photoconductors is the limited dynamic range. Despite this, the overall instrument dynamic range requirements can be met by employing other design elements to enable both faint and bright source observation.

SRON, Cardiff University and CESR have established a collaboration to develop a TES bolometer system suitable for ESI. SRON has experience with TES bolometers arrays with FDM (Frequency Division Multiplexed) readout for space x-ray instrumentation. This is of direct relevance to ESI as there is a large technology overlap between FIR and x-ray TES detectors and read out electronics. The large investments made in XEUS detector development have benefited the ESI programme through technology transfer. Any further XEUS development work at SRON would be expected to bring added benefit to ESI.

Prototype detectors adapted to FIR requirements have been fabricated and tested by SRON and Cardiff (Figure 21). SRON have successfully tested a device at 205 mK. The results indicate that an NEP ~ 4×10^{-19} W/√Hz would be obtained for a system operating at 100 mK. Cardiff has a large amount of experience in FIR space astronomy and will take the lead on testing the detectors. CESR in Toulouse is working on the design and development of ASIC devices to bias and readout the detectors. It is considered necessary to adopt ASIC technology for parts of the detector bias and readout system in order to meet the mass and power budgets. Work is continuing to bring the maturity of the entire detector system ready for the 2009 detector technology selection process (see §**Error! Reference source not found.**).

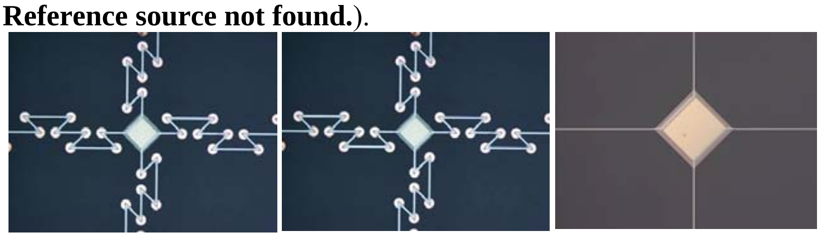


Figure 21 – Various prototype ESI detectors tested at SRON. The detector on the right demonstrated close to the goal performance.

Sub-K Cooler: The instrument cooler architecture has also been studied in depth by the ESI consortium. A hybrid ^{3}He sorption cooler / Adiabatic Demagnetisation Refrigerator concept has been proposed which can provide continuous cooling power to the detector system below 100 mK. This system has the key advantage of being very compact and light-weight when compared with other systems. One of the key challenges of this architecture is limiting the heat rejected by the instrument cooler to the spacecraft cooler during recycle. CEA SBT is currently carrying out a strategic development programme for such cooler systems for future space science experiments including XEUS and SPICA. The most recent tests have achieved a base temperature of 75 mK. Future developments over the next two years are expected to yield a space qualifiable system. It should also be noted that ISAS have flight heritage with ADR coolers and have achieved a bath temperature of 60mK in orbit.

Photoconductors/Si-Bolometers: The heritage for the photoconductor detector systems is based on direct experience gained from Herschel, AKARI and indirectly from SPITZER for the Si:Sb technology. The ESI consortium have successfully tested stressed Ge:Ga detectors suitable for ESI to gain information on the behaviour of the devices under very low stray-light conditions and under p+ irradiation. IMEC are currently developing a Direct Injection amplifier ASIC based on 0.35 μm technology to be mounted directly on the photoconductor crystal suitable for use in ESI (i.e. very low dissipation/noise/dark current/well depth). It is expected that a prototype of this ASIC will be demonstrated during the summer of 2007.

LETI and CEA have recently started a collaboration on antenna coupled Si-bolometers. This work is based on an evolution of the PACS bolometer detectors. The key feature of this work is that the photons are coupled into the detector circuit with a tuned micro-fabricated bow-tie antenna which is capacitively coupled to the absorber. This technology could be considered a candidate for use on ESI if significant rapid advances were made within the timescales available to ESI.

4.3.3 Compliance with Spacecraft Interface Requirements

Feasibility studies to date show that ESI is compatible with the resources and interface data summarised above in Table 2. Information on the results of instrument assessment studies to date are summarised below.

Structural design: A first order instrument layout has been made. The main structure of the instrument is likely to be fabricated from a structural form of SiC to match the CTE of the instrument optical bench. Estimates of the instrument mass and the volume have been made and are broadly consistent with the values quoted in Table 2.

Optical design: The optical layout shown in Figure 20 incorporates a folding mirror which amplifies the optical path difference between the two arms of the spectrometer by a factor of eight as the mirror is scanned. The design provides diffraction limited imaging at 40 μm. Other challenges in the optical design of the instrument include; (1) the performance of the beam-splitters over a wide spectral range - prototype beam-splitters are under development at Cardiff University, (2) stray-light analysis and control considering the extreme sensitivity of the detectors, and (3) the optimization of the design to minimise the number of mechanisms required in the instrument.

Mechanisms: The instrument will require at the very minimum, a mirror scan mechanism which dissipates very little power inside the FPU, has a scan length of the order of 100mm (goal) and is mechanically robust. A design exists for a scan mechanism which meets these general requirements which was qualified for a cryogenic FTS instrument GIRL (German Infrared Laboratory) instrument that was to be flown on Spacelab. Apart from the scan mechanism, a filter wheel and beam steering mechanism are likely to be required.

Thermal design: The key element of the instrument thermal design is the development of a sub-K cooler if TES detectors are selected. The detector box inside the instrument will be cooled to 1.7 K and will therefore be thermally isolated from the main ~ 5-K chassis. The thermal loads onto the cryogenic thermal stages will have to be strictly controlled to minimise both the dissipation and the static thermal parasitic loads. The fact that SPICA will be launched warm makes this somewhat simpler as differential CTE between structural components can be exploited to thermally isolate different thermal stages after launch.

OBDH: The current baseline for the ESI DPU is to utilise a SPARC V8 compliant Leon3FT FPGA processor. Depending on the details of the particular detector options finally adopted for ESI, each frame will be in the order of 12 kbytes (uncompressed). The baseline architecture for ESI is to convert the TM into packets inside the instrument DPU then port them to the spacecraft CDMU via a Spacewire link for storage in bulk memory before down-link. The DPU could be used to perform lossless compression of the TM if required.

4.3.4 Current heritage and Technology Readiness Level (TRL)

The ESI consortium is composed of scientists and engineers with much experience in building and operating space IR instrumentation on programmes such as IRAS, ISO, Herschel, Planck as well as AKARI. All individual components of the proposed instrument have been demonstrated to function and perform in a laboratory environment at TRL 4 or greater. Many pieces of technology have been qualified and flown and thus have a TRL

9. As far as the qualification of the integrated instrument is concerned, routine work is required to bring the integrated instrument to a flight ready TRL 8.

4.3.5 *Proposed procurement approach & international partners*

The instrument is to be developed under the leadership of a European PI who will be responsible for guaranteeing the scientific performance of the instrument and its delivery within the overall schedule and financial constraints. Significant contributions to the instrument development are expected to come from Belgium, Canada, France, Germany, Italy, the Netherlands, Spain and the UK and possibly Japan[*]. Each institution collaborating on ESI will have a nominated Co-I to manage the work packages for that institution. A Business Agreement signed by at least the PI and Co-I will be drafted to define the responsibilities of each Co-I institute. A Multi-Lateral Agreement (MLA) will be agreed by the entire consortium (see also §**Error! Reference source not found.**). ESI consortium institutes will be funded by their national funding agencies. In all cases, these funding agencies are already aware of SPICA and the intention of European scientists to contribute a FIR instrument to the mission. The ESI consortium has been studying the scientific potential and technical requirements for nearly three years and we have established that the technical capability exists within the ESI consortium to deliver the instrument and its constituent subsystems. In most cases, multiple institutes are technically capable of supplying the elements of the instrument. Table 5 shows the list of institutes which have expressed an interest in making contributions to ESI. The final work breakdown structure will be made at a later stage when the instrument design is more mature and the funding situation known in detail.

Scientists from NASA JPL with experience in space infrared instrumentation have recently expressed the desire to join the ESI consortium with the view to making a hardware contribution. The decision of whether or not to include NASA in the ESI consortium will be made following the selection of SPICA under the Cosmic Vision programme, and will be based on an assessment of the balance between the added value of a US contribution and any additional managerial complications and technical or programmatic risks.

Element	**Potential Co-I Institutes**
Analogue Electronics	CEA Saclay, MSSL UK, SRON Utrecht, IAC and CSIC Spain
TES Digital Electronics	CESR Toulouse, Obs. Bordeaux
Bolometer Detectors	SRON Utrecht and Cardiff University for TES , CEA/LETI for Si-Bolometers
Instrument calibration	RAL UK, IAS Paris, Cardiff University, University of Lethbridge
Cryogenic analogue electronics	IMEC Belgium
DPU and Onboard Software	IFSI INAF Rome
EGSE	RAL, KU Leuven
Instrument AIT	RAL UK, U. of Lethbridge, IAS Paris, MPE Garching, Cardiff University
Instrument ground segment + data processing	RAL UK, Imperial College, U. of Sussex, Open University, IAS Paris, INAF Italy, CESR, OAMP, KU Leuven, CSIC Madrid, Cardiff University
Mechanisms	MPE Garching, IAC Tenerife, ATC Edinburgh, RAL UK, MPIA Heidelberg, SRON
Optical elements	Cardiff University (calibrators, filters etc.), MPE Garching, OAMP mirrors
OGSE	RAL UK
Photoconductor Detectors	MPE Garching, KU Leuven, University of Lethbridge, MPIK Heidelberg, ISAS Japan, University of Tokyo, Nagoya University
PI Institute + Project office	RAL UK
Science	All institutes in the ESI Consortium
Structure	MPE Garching, MSSL UK
Sub-K Cooler	CEA-SBT Grenoble

Table 5 – Possible instrument development responsibilities for ESI consortium

ESA Systems Engineering and Management of ESI: Whilst the ESI instrument is to be largely funded by national agencies, we propose that ESA undertakes a significant role in the ESI management and system engineering, and assume formal responsibility for the delivery of ESI to JAXA. The rationale behind this proposal is that ESA is well placed to negotiate the interfaces for the ESI consortium, to oversee the spacecraft/instrument tradeoffs, to monitor the progress of the instrument development and to act as the formal point of contact with JAXA. This is similar to the manner in which ESA is involved in the MIRI instrument for JWST. An ESA project scientist would be nominated to work alongside the engineering team to monitor the projected/actual scientific performance of the instrument throughout the development programme. ESA engineers/scientists would participate in the periodic project reviews.

[*] Japan would be expected to make significant hardware contributions if the photoconductor detector option is selected.

4.3.6 Critical issues

The critical issues requiring focused attention during the development programme are outlined in Table 6.

Critical Issue	Comments
Thermal budget	The design of the instrument must take into account the end-of-life performance of the entire instrument and spacecraft thermal systems. Close management and detailed verification of various contributions to the thermal budget will be required.
Signal integrity	The extremely high sensitivity of the ESI detectors and the vanishingly low background from the SPICA Telescope Assembly will mean that strict control of various types of interference will have to be carefully managed and controlled. These include EMC, cross-talk, microphonics and stray light.
Mass and power budgets	The mass of the ESI FPU (and of the other instruments) will need to be carefully controlled. This is due to the strong system design driver to minimise the mass of the Telescope Assembly and integrated instrument suite which is on a thermally isolated stage at ~5 K. Another system design driver is for minimisation of the dissipation within the warm electronics on the service module due to the limited scope for deep space radiators to reject the dissipated heat.
Detector array accommodation	Both the stressed Ge:Ga and the TES bolometer pixels dimensions are relatively large due to the mechanical implementation of the stressing mechanism in the photoconductor and the requirement for thermal isolation of the absorber from the bolometer heat sink in the TES. This makes the optical design of the camera optics less compact and more difficult to control.
TES Detector System Issues	The various sub-systems of the TES detector option need to be demonstrated to achieve the overall instrument requirements within the allocated resource allocations

Table 6 – Critical issues in the development of the ESI instrument

4.4 MIR Camera and Spectrometer

The SPICA MIR instrument has two basic modes; a wide-field imaging camera mode and a spectrometer mode. Si:As detectors are used for $\lambda < 27$ μm and Si:Sb detectors for $\lambda > 26$ μm. A tip-tilt mirror is shared with the Coronagraph to correct fine pointing errors.

Camera mode: The wide-field camera has four channels to cover the wavelength range (5 to 38 μm). Pixel scale of imager (P_{FOV}) is optimized for the shortest wavelength (λs) at each channel, that is $P_{FOV}=\lambda s/D/3$. The imager has several band pass filters and a grizm for low resolution objective spectroscopy (R~200). Specifications of imager are as follows:

	Wavelength coverage	Pixel FOV	Total FOV	Detector
Channel 1	5 – 9 μm	0.098”	100” (Optional:300”)	Si:As 1k x 1k (Optional:3x3mosaic)
Channel 2	8 – 15 μm	0.16”	160” (Optional:320”)	Si:As 1k x 1k (Optional:2x2mosaic)
Channel 3	14 – 27 μm	0.28”	280”	Si:As 1k x 1k
Channel 4	20 – 38 μm	0.39”	400”	Si:Sb 1k x 1k

The longest wavelength of each channel must be shorter than the twice of the shortest wavelength to avoid higher order mixing while using grism. Using dichroic beam splitter, the FOV of Channel 1 is within the Channel 3 FOV and similarly the FOV channel 2 is within the FOV of channel 4. A possible extension of the channel 1 and 2 FOV is under assessment – this is indicated as an option in the table above and Figure 22.

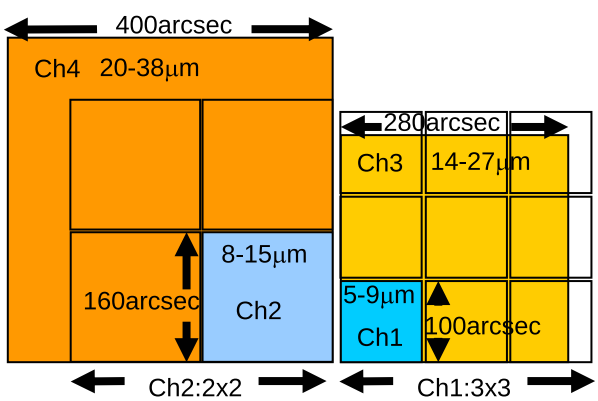


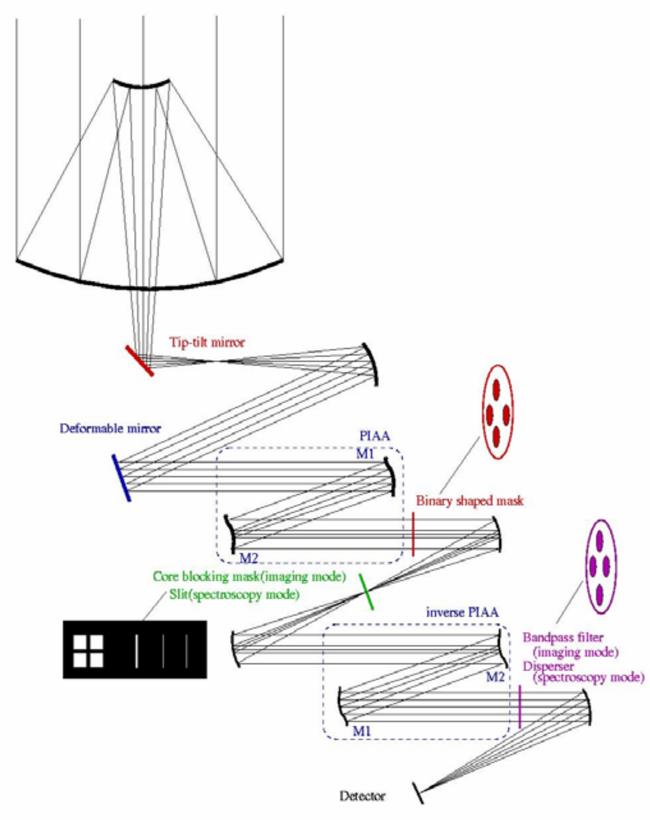
Figure 22 – Focal plane allocation for the MIR imager

Spectrometer mode: The Spectrometer is a long slit grating spectrometer with an Integral Field Unit. It has four channels to cover the wavelength range. In the shorter wavelength region (λ < 15 μm) an immersion grating is used to achieve a spectral resolution of R~30000. The slit width of each channel is tailored for the longest wavelength to avoid diffraction losses. Slit length and number is limited by the number of pixels and wavelength coverage at each band. Consideration is being given to the provision of high resolution Fabry-Perots (R~30000) to cover the 17 and 28 μm H_2 lines. The specifications for spectrometer are as follows:

	Wavelength coverage	**Slit width (=2xP_{FOV})**	**Slit length**	**Number of slices**	**Resolving power**	**Detector**
Channel 1	5 – 9 μm	0.53”	2.7”	3	30000	Si:As 1k x 1k
Channel 2	8 – 15 μm	0.88”	4.4”	3	30000	Si:As 1k x 1k
Channel 3	14 – 25 μm	1.5”	20”	5	6000	Si:As 1k x 1k
Channel 4	20 – 38 μm	2.2”	40”	8	3000	Si:Sb 1k x 1k

The instrument will be developed by a Japanese / South Korean consortium.

4.5 MIR Coronagraph



Parameter	**Specification**
Core wavelength (λ)	5−27 μm (3.5-5 μm optional extension)
Observation mode	Imaging, Spectroscopy
Coronagraphic mode	binary shaped pupil mask, hybrid(binary shaped pupil + PIAA)
Inner working angle (IWA)	~ 3.5 × *λ/D* (binary shaped pupil mask mode) < 2 × *λ/D* * (hybrid mode)
Throughput	~30% (binary shaped pupil mask mode) ~80% (hybrid mode)
Outer working angle (OWA)	~ 30 × *λ/D* * (binary shaped pupil mask mode) ~ 10 × *λ/D* * (hybrid mode)
Contrast between IWA and OWA	≥ 10^6
Detector	1k × 1k format Si:As array, 0.1”/pixel
Field of View	1’ × 1’
Spatial resolution	< IWA
Spectral resolution	~ 200

Figure 23 - Schematic optical layout of the Coronagraph and key specifications

The Coronagraph instrument is used to carry out high contrast observations by suppressing the side lobes of the PSF of a bright source (i.e. a star) enabling observation of companion objects (e.g., planets and proto-planetary disks). The instrument wavelength range is 5-27 μm with a possible extension to 3.5-5 μm. The instrument has two observation modes; imaging and R~200 spectroscopy. The key specifications of the SPICA coronagraph and a schematic view of the optical layout are shown in Figure 23. The contrast requirement is 10^6 to detect exo-planets directly in the MIR. Realising such high contrast is very challenging and we plan to develop two coronagraph methods. The first uses a binary shaped pupil coronagraph, which is regarded as the most simple and robust approach. Laboratory demonstrations of this method have already been successfully done with visible light and a 10^7 contrast has been confirmed in the experiment. The second method uses a hybrid technique of phase induced amplitude apodisation (PIAA) and binary shaped pupil. The advantage of the hybrid solution over the shaped pupil method is that the inner working angle (IWA) is reduced from ~ 3.5 λ/D to < 2 λ/D. Another advantage of the hybrid solution is an improvement in throughput from ~30% for the shaped pupil only method to ~ 80 % for the hybrid method. Although the hybrid solution requires more complicated optics than the shaped pupil mask only method, a contrast better than 10^6 has been experimentally demonstrated with visible light. The instrument will use an adaptive tip-tilt mirror for fine pointing corrections and final correction of the telescope and instrument input optics WFE will be carried out with a deformable mirror at the input to the coronagraph. The Coronagraph is being developed by a Japanese consortium.

4.6 BLISS, a Proposed US-Built Grating Spectrometer.

A US group centred at JPL is proposing a moderate-resolution compact FIR to submm grating spectrometer, BLISS, for SPICA. BLISS been under study for 3 years and is envisioned as a sensitive suite of grating spectrometers optimized for broadband spectroscopy of distant galaxies. This sensitive point-source capability will complement the core spectral imaging capability of ESI by extending the wavelength coverage to meet the wavelengths accessible from ground based facilities. The combination will make SPICA an even more powerful probe of galaxy evolution in the early universe. We note that the BLISS instrument is under development as an entity distinct from the potential US hardware contribution to ESI described in §4.3.5.

4.7 SPICA Telescope Assembly (STA)

4.7.1 Description and key characteristics

The key features of the STA are:

1. A two-mirror on-axis design with a 3.5 m monolithic primary,
2. An operating temperature below 5 K with warm launch,
3. Diffraction limited performance at 5µm over the central portion of the field of view

The STA comprises the primary and secondary mirrors, the support structure for the mirrors, the telescope optical bench and the structural support structure. A refocusing mechanism is incorporated as a part of the secondary mirror support to compensate for any errors introduced during launch and/or telescope cool-down. A schematic layout of these items is shown in Figure 24. A list of the key specifications and requirements of the STA is given in Table 7.

Parameter	Baseline specification / requirement	Comment
Telescope configuration	2-mirror on-axis Ritchey-Chrétien	Compact proven design with wide useable field of view with good image quality
Operating temperature	< 5 K	Obtained via passive radiative cooling (to deep space) + mechanical cooler after initial warm launch
Collecting area	3.5 m diameter	Pupil stop on secondary mirror M2. Clear aperture>3.4 m
Effective focal length	18m	Leads to focal ratio of ~5.2 with 11,46"/mm plate-scale at telescope focal plane (TFP)
M1-M2 separation	Baseline 3m	To maintain compactness of overall assembly; requires fast primary mirror
Back focus	Baseline 0.8m	Minimum distance to accommodate M1 support structure and focal plane instrument optical bench
Field of View	0.5° diameter	Large FOV to be shared by instruments taking separate parts of the field
Image quality	Diffraction limited at 5µm (at operating temperature)	Strehl ratio > 80% at 5µm this is equivalent to wave front error (WFE) < 350nm rms in central part of the accessible field of view Surface roughness requirement of < 20nmRMS
Mirror Reflectivity	> 97.5% above 30 µm > 95% below 30 µm	This includes particulate contamination effects
Mechanical accommodation	Mass < 700kg Static design load: 20 g First mode: >60Hz Volume: ø3500mm cylinder with ~ 1:1 aspect ratio	These figures are the results obtained from ISAS assessment studies. The mass budget e excludes the mass of the instrument optical bench.
Thermal	Mirror temperature temporal stability: <0.25K/h Max temperature differential across primary: 0.5 K (TBC) Static heat load: ~ 13mW	The temperature stability requirement limits fluctuations of in-field background emission at long wavelength. The heat load budget and temperature differential requirement provides for thermally-induced local deformations degrading optical performance

Table 7 – Key specifications/requirements of the Telescope Assembly

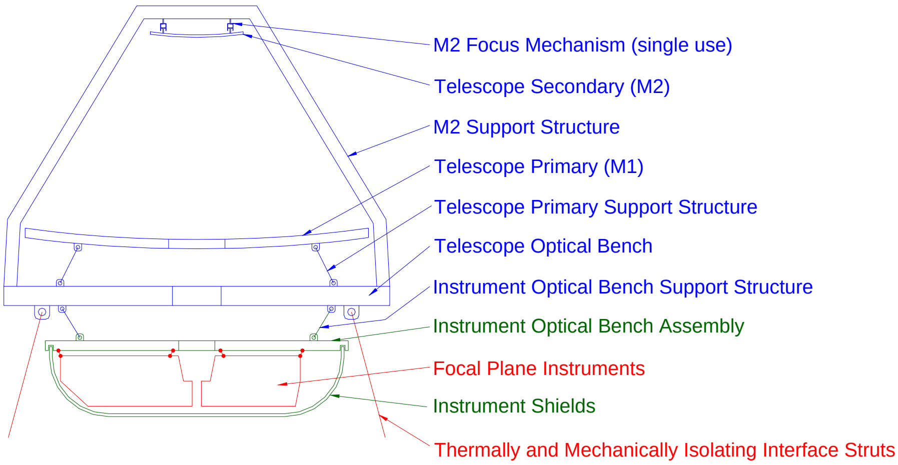


Figure 24 –Schematic representation of the SPICA Telescope Assembly showing proposed ESA funded deliverables in blue, non-ESA deliverables in red with the responsibility for the Instrument Optical Bench Assembly in green.

The central 30' diameter of the full field of view is expected to be well corrected for aberrations. The overall 350 nm RMS WFE specification means that diffraction-limited imaging can be achieved with all the SPICA instruments, including the MIR instrument. The compact telescope design requires a relatively large central obscuration (5%) due to the relatively large M2 diameter. Additional secondary support struts will add to this entrance pupil obstruction which will cause about a 10% total loss in throughput. The baseline is to use four struts spaced at 90º for the M2 support structure. The sidelobes introduced into the PSF by this configuration are highly symmetric and permit the coronagraph to achieve high contrast ratios.

4.7.2 Performance assessment with respect to science objectives

One of the main design drivers for the telescope is the requirement for diffraction limited imaging at 5 µm. This requirement defines the derived mirror surface errors budgets which can be split into three different spatial frequencies of the telescope pupil as follows:
Low-spatial-frequency error budget: Overall STA WFE to be < 350 nmRMS which can be broken up into two equal components: focus (< 250 nmRMS) and higher order aberrations (< 250 nmRMS). In addition, the overall peak-to-valley must be less than 0.563 µm for each mirror. The focus requirement limits the defocus to +/- 0.185mm at telescope focus.
Mid-spatial-frequency error budget: These errors arise from residual high frequency surface errors, for example mount induced stress, print-through effects or general substrate structure. Depending on periodicity and correlation length they can dominate the PSF diffraction rings around 10 to 50λ/D which fall into the IWA to OWA optimal rejection range of the MIR coronagraph. The requirement is to be < λ/80 per mirror or 62.5 nmRMS. Additional limits are to be set on the peak-to-valley and spatial frequency range.
High-spatial-frequency error budget: These errors arise mostly from mirror surface micro-roughness, cracks and small local defects in coatings all of which induce large scale/wide angle scatter. The specification translates into a < 20 nmRMS specification for each telescope mirror surface.

4.7.3 Testing requirements

The verification and performance testing of the STA will be challenging. The joint ESA/JAXA/Industry Telescope working group will need to define how and where each step of the process will be carried out. A possible split of responsibilities which has been discussed with the SPICA working group is as follows:
Pre-delivery: Standard room temperature space environmental testing, acoustic and vibration tests. Optical testing at < 100 K. (Note: it would be preferable to perform this optical verification closer to the normal operating temperatures if such a capability readily existed in Europe).
Post-delivery: Final optical verification of the STA at operating temperature by JAXA. European support for the specification and execution of this test is desirable.

The issue of verification of the alignment and WFE in a 1-g environment is open and will need to be addressed during the assessment study. One possible approach would be to implement a system of g-cancellers during optical verification in order to simulate a zero-g environment. Another approach would be to use FEA to model the deformation of the optical surfaces under 1-g and verify telescope performance against this deformed shape rather than the required shape of the telescope in zero-g. The validity of this approach would depend on the accuracy of the modelling of the shape of the deformed mirror under 1-g.

4.7.4 Special Requirements

Mirror surface cleanliness: The nominal baseline molecular contamination specification is for BOL: < (400+/-50)C. This limits the increase in mirror emissivity and controls the presence of spectrally important MIR or FIR ice bands. A particulate contamination specification of 400 or 0.26% geometric obscuration ratio limits surface scatter from the telescope mirrors in the MIR range, stray-light paths to the sky or surrounding telescope structure via near-specular and wide angle scattering in the FIR.

4.7.5 Current heritage and Technology Readiness Level

The material baselined for the STA is silicon carbide; chosen for to its excellent material properties of high specific strength, stiffness and thermal conductivity, low CTE, excellent cryogenic stability and the ability to be polished and coated with low emissivity metallic films. This material benefits from the established experience and design heritage in Europe for manufacturing silicon carbide cryogenic space optical elements. In particular the Astrium-France Herschel (3.5 m, 80 K, WFE < 6 µm), ALADIN (1.5 m, WFE < 150 nm) and GAIA (1.5 m x 0.5 m, WFE < 20 nm) telescopes as well as the ECM-Germany SPICA Breadboard mirror, NIRSpec optical bench[†] and an 800mm, 4 kg ultra-lightweighted mirror produced under the ESA Future Technology programme. This European heritage is complemented within the Japanese SPICA consortium by the experience with the AKARI telescope and several JAXA sponsored SPICA telescope studies using sub-scale breadboard models which were used to assess characteristics such as machinability, residual porosity and roughness and surface form variations under cryogenic cycling as well as the optical performance of different silicon carbide materials: SiC 100, HB CeSiC or hybrid C/SiC and reaction sintered and NT-SiC.

4.7.6 Proposed procurement approach & international partners

The final procurement and partnership agreement is for negotiation between ESA and JAXA, however we offer the following as an approach that might be considered as a starting point. The initial technical specifications and requirements for the Telescope Assembly will be refined during the ESA and Industrial assessment studies for the telescope system in conjunction with the Telescope Working Group. These specifications and requirements would form the basis of the formally agreed procurement documentation, agreed by JAXA and ESA, to be released by open European ITT for the definition and implementation phases of the procurement process. The tenders will be formally assessed by ESA for compliance with JAXA providing comments. Two European companies (Astrium France and ECM Germany) have carried out assessment studies on the STA under contract to JAXA including the manufacture of bread board mirrors. The results of these studies are documented in open literature[87, 88]. Both of these companies have reviewed an outline STA specification and have expressed a strong interest in participating in SPICA.

Various system level technical tradeoffs will be necessary regarding the design and implementation of the telescope assembly. These issues are to be addressed within the scope of the eventual European industrial assessment and definition studies. The spacecraft Phase-A study currently overlaps both of these European study phases which permits iteration between Japan and Europe on the optimisation of the telescope assembly and spacecraft architecture under the auspices of the Telescope Working Group (See §**Error! Reference source not found.**).

4.7.7 Critical issues

The following critical issues related to the telescope system have been identified:

1. Overall design trade-off between support structure complexity, structural/thermal stability and mass.
2. M2 tip-tilt and piston mechanism.
3. Optical surface error budget (from low to high spatial frequency) of telescope mirrors.
4. Ground testing: characterisation of the telescope system (optical/thermal/structural) under flight representative environment conditions (deep cryogenic operation, gravity compensated, high cleanliness)
5. Model philosophy: The agreed model and spares philosophy needs to be agreed by ESA and JAXA during the assessment studies.

[†] Fully flight qualified prototype model produced under contract to ESA

5. SPICA Spacecraft

The layout of the SPICA spacecraft is schematically illustrated in Figure 25. The main elements of the spacecraft include the Telescope Assembly (including instrument suite), sunshield/stray-light baffles, solar array and the spacecraft bus. The Telescope Assembly and instrument suite are cooled to < 5 K with a system of mechanical cryocoolers and passive radiative cooling. This obviates the need for a heavy cryostat and a store of consumable liquid cryogens to provide cooling capacity and means that the total mass of the spacecraft is kept to 2600 kg including 180 kg of propellant. This approach also has the benefit of a warm launch for the payload which makes environmental vibration qualification simpler and opens up the possibility of employing engineering solutions for thermally and mechanically efficient cryogenic structures.

Thermal subsystem: Two separate Joule-Thompson (J-T) coolers are used for active cooling of the Telescope Assembly and instruments. The working fluid in both J-T coolers is pre-cooled by a 20-K Stirling cooler which allows an ultimate temperature of 1.7 K for the ^{3}He J-T cooler and 4.5 K for the ^{4}He J-T cooler.

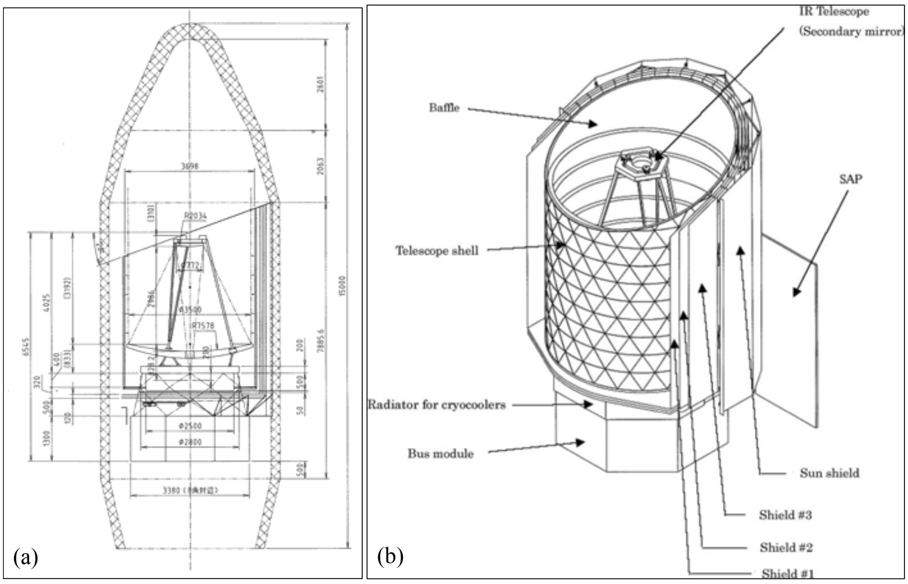


Figure 25 - Architectural layout of the SPICA spacecraft; (a) stowed in the H2A fairing and (b) 3D cut-away view illustrating the thermal stages.

The total 4.5 K heat load budget for the telescope assembly and instrument suite, including wiring and structural parasitics, radiation and dissipation within the instruments is 28 mW. The development cooler has demonstrated a maximum heat lift capacity of 50mW at 4.4 K (BOL performance) under representative flight conditions with a total primary power consumption of less than 160 W. The heat load budget for the 1.7 K stage of the ^{3}He J-T cooler is 5 mW which is allocated to cooling the ESI detector subsystem. This cooler has demonstrated a heat lift of 16 mW @ 1.7 K (BOL performance). The high temperature heat load from the coolers is radiated to space with a system of loop heat pipes and radiator panels. The Stirling cooler is based on AKARI heritage and is under development to upgrade the heat lift capacity. Similarly, the J-T coolers are based on an upgrade of the JAXA JEM/SMILES cooler.

A critical aspect of the thermal design is the cool-down of the payload assembly from ambient temperatures at launch to the cryogenic operational temperatures. It is currently baselined to use a Stirling pre-cooler to ensure the payload elements reach a temperature below the J-T coolers pinch point before they are switched on. The current analysis indicates that the telescope will reach operational temperature 170 days after launch.

Power: The solar array and power control and distribution system are sized to provide 2.4kW (EOL) of primary power to the instruments and spacecraft subsystems. The main spacecraft bus provides unregulated power to the subsystems at voltages between 32.5 and 52V.

CDMS: The spacecraft CDMS uses a Spacewire bus for instrument and spacecraft subsystem interfaces. The mass memory has sufficient capacity to buffer all instrument and spacecraft telemetry for a 24 hour period. Sufficient Fault Detection, Isolation and Recovery functions are implemented by the spacecraft and instruments to safe the space segment in the event of an anomaly occurring when the spacecraft is not in direct communication with the MOC.

AOCS: The expected pointing error is less than 1” and the stability is less than 30 mas. Higher accuracy will be achieved for the coronagraph by using an internal tip-tilt mirror. Microvibrations from spacecraft mechanisms will be carefully managed and controlled during the satellite development.

6. Ground segment / science operations and archiving

The prime ground station is located at Usuda in central Japan. It is proposed that it be supported by the Cebreros ESA ground station providing SPICA with two ground contact periods each day (~ five hours for each station). During the daily contact period with Usuda, the mission timeline for the following 24 hours will be uploaded to the spacecraft although Cebreros could also be used as a backup. The telemetry stored in spacecraft mass memory will be down linked to the ground stations at each contact period. With the Usuda and Cebreros ground stations, the total TM capacity would be around 60 GByte/day. The spacecraft and instruments will have sufficient autonomy functions to be tolerant to the loss of ground contact for extended periods of time. It is envisaged that the Cebreros station will not be available from time to time when the facilities are required to support other ESA programmes. This would temporarily restrict scientific operations but would not significantly compromise the scientific return of the mission.

The SPICA Mission Operations Centre (MOC) is to be located and operated in Japan by JAXA/ISAS and will be responsible for spacecraft operations. The MOC will provide the SPICA Science Operations Centre (SOC) science telemetry and combine the instrument and spacecraft commands into the harmonised common telecommand timeline for upload to the spacecraft.

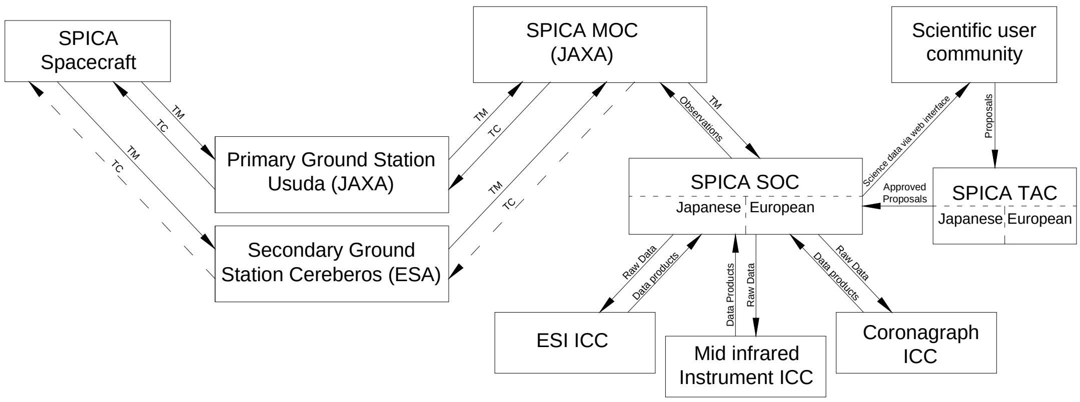


Figure 26 – Overall ground segment organisation

6.1 SPICA Science Operation Centres

A Science Operation Centre (SOC) located in Japan will be responsible for Japanese observation time science operations. We propose that ESA makes significant contributions to support SPICA by running a second (European) SOC located at ESAC responsible for European observation time science operations. This contribution would assist European scientists to fully exploit the unique capabilities of the spacecraft and help guarantee the scientific success of the mission. The roles of the two SOC include:

User Support: making available the necessary tools for the scientific community to prepare proposals.

Proposal handling: technical assessment of proposals and support of the Time Allocation Committee.

Observation planning: scheduling observations, optimisation and validation of instrument and spacecraft telecommands to be uploaded via the MOC

Data processing, archiving and distribution: coordinating with the Instrument Control Centres, the processing of science and housekeeping telemetry into data products and making them available to observers.

6.2 Instrument Control Centres (ICC)

Instrument Control Centres (ICC) will be established for each of the SPICA instruments. They will support the development of the instruments, especially the instrument testing and calibration (pre and post delivery). They will provide the necessary software to process the instrument data (data pipelines) and generate the calibrated data products, develop tools to enable interpretation and viewing of data, have responsibility for monitoring the health of the instruments (trending) and responding to instrument anomalies. To ensure that a good knowledge of the operation of the instrument and spacecraft is embedded within the Japanese SPICA operations team and the

European ESI instrument team, members of each team will be seconded to work for extended periods in the partner institutes at various times. It is expected that a significant proportion of the set of Herschel tools will be able to be reused for ESI. Some members of the ICC will be based at the SOC during the commissioning, preliminary verification and operations phases of the mission.

6.3 Time Allocation

The allocation of observing time on the spacecraft will be managed by two separate time allocation committees (TACs). Nominally 15% of the mission is required for engineering and maintenance operations and therefore 85% of the time will be available for science operations. A Japanese TAC will be allocated 75% of the observing time while the European (ESA) TAC will be responsible for the remaining 25%. The majority of the Japanese time will be for (non-European) open time programmes, while the remaining Japanese time will be guaranteed time for members of the Japanese SPICA programme. The majority of the European time will be allocated to European open time programmes with a small portion of the time allocated to members of the ESI consortium.

The philosophy for the proprietary data period is to make the science data available to the wider scientific community as soon as possible. The exact details have not been agreed, but the ESA requirement that the data be made publicly available within one year will be met.

7. Key Technology Areas

The critical hardware items within the SPICA payload are listed in Table 8.

Item	Comment	TRL
Spacecraft coolers	J-T and Stirling coolers based on upgrades of coolers qualified for (JEM/SMILES). Laboratory tests have demonstrated heat lift capacity exceeding requirements at BOL in representative laboratory tests. Cooler life testing programme commencing 2008	5
SPICA Telescope Assembly	The technical difficulty in developing the SPICA Telescope Assembly is judged to be less difficult than existing optical/NIR cryogenic programmes. The technical development would be carried out by European industry under contact to ESA.	5
ESI TES Detector System	ESI programme greatly assisted by benefiting from direct technology spin off from XEUS developments. Key technical challenge of thermal isolation of bolometer has been demonstrated in the laboratory. Ongoing development programme by SRON, Cardiff University and CESR.	4
ESI Sub-K cooler	Ongoing parallel development activity within Europe to develop ADR coolers for XEUS and SPICA and other ESA science missions. CEA SBT has an ongoing development programme	4
ESI Photoconductor	The Ge:Ge and Si:Sb BIB detectors have extensive flight heritage (TRL 6). IMEC Belgium developing and testing low-power/low-noise ASIC readout chip suitable for ESI. Characterisation of the device planned for 2007 (TRL 4)	4/6
ESI FTS scan mechanism	The design of the GIRL mechanism has direct applicability to ESI. It is planned to cryogenically test the mechanism by the ESI consortium	6
MIR & Coronagraph Instrument Detectors	The detectors are commercially procured from the US. The currently available technology has been tested and meets the SPICA performance requirement however the array format needs to be increased.	6
Coronagraph deformable mirror	An enabling technology for the Coronagraph is the deformable mirror. This will be commercially procured from Boston Micromachines Corp after adapting existing technology for large stroke and cryogenic use.	4

Table 8 – Critical SPICA payload technology readiness summary

8. Communication and outreach

Communication: SPICA is an observatory-class mission, and will be used by a large international community. We will develop a comprehensive website to disseminate all mission-relevant information and background to the user community. We will organise workshops pre-launch to aid astronomers in proposal preparation, and during the mission to update the community both on science achievements and mission developments.

Outreach: Space missions and the science questions that they address hold a unique fascination with the general public, and the themes highlighted in this current Cosmic Vision call will be no exception. We will work with the ESA Science Communication Office, national science communicators and national funding organisations/public engagement schemes (e.g. Royal Society, Aiwa friendship programme) to publicise SPICA and its science through a programme of public engagement activities designed to appeal to/satisfy the scientific curiosity of a broad cross-section of the general public. Activities will include:

- A public website detailing the SPICA mission, its science goals and the technology used to realise the satellite and its instrument suite. Website material will target a wide range of audiences, including the casual websurfer, the interested member of the public, school students/teachers and the amateur astronomer.
- Presentation material for use by scientists and engineers working on aspects of the mission to use to give public talks and lectures on SPICA and its science
- Mission launch and early science press releases
- Educational resources for pre-University school students across the ESA member states and Japan, designed for integration into the mathematics, science, engineering & technology and citizenship curricula. Resources will include investigations, problem/work sheets, practical experiments, career case studies, and material around which group/classroom discussions can be based. Drama-based shows and activities to engage primary/early-stage school children in science/ engineering activities

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10. References

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