Conceptual Design Study for an Imaging Far Infrared Spectrometer for SPICA

Study Report April 2005

Edited by
Bruce Swinyard
Rutherford Appleton Laboratory
Chilton Didcot
Oxon
U.K.
OX11 0QX

B.M.Swinyard@rl.ac.uk
+44 (0)1235 446271
Executive Summary

With its 3.5-m cooled mirror, the SPICA mission promises an enormous advance in sensitivity in the Far Infrared (FIR) region compared to all previous or planned missions. Among the most significant benefits of this sensitivity improvement will be that it will be possible for the first time to carry out detailed FIR spectroscopic investigations of galaxies, both local and at high-redshift, and of the formation of planetary systems in our own galaxy. These are two of the most important areas of contemporary astrophysics, and they require the unique capabilities of SPICA. We propose to carry out a detailed study of a FIR imaging spectrometer for SPICA, with a design optimised for these science goals.

With SPICA, it will be possible to carry out spectroscopic observations on a large proportion of galaxies (all those with L_{FIR} > 10^{10} L_{\odot}) with redshifts up to z ~ 2 and on the brightest of objects out to z > 5. Uninterrupted access to the whole 25 to 200 \( \mu m \) region means that we will be able to study the objects that gave rise to the formation of most of the stars we see in the local Universe today. No other wavelength range is capable of providing this diagnosis as only in the FIR do we see both the ionised lines and the FIR cooling lines associated with star formation that fully characterise the type of galaxy, its power source (AGN, starburst, and/or old stellar radiation field) and therefore the UV field, the metallicity and star formation rate. This ability is critical to establishing an understanding of both the nature of the Cosmic Infrared Background, the evolution of galaxies, and the history of element production from the initial epoch of galaxy formation to the present day. SPICA may also offer the first possibility of detecting molecular hydrogen cooling lines from the precursors of the very first stars as they condensed from clumps of hydrogen and helium gas produced in the big bang.

The SPICA mission will also add considerably to our understanding of the origins of planetary systems and how they arise in the process of star-formation. In particular the access to the “missing” octave from 25 to 60 \( \mu m \) that is not covered by present or other future missions will allow us to determine the nature of the dust from which planets form around stars. The dust and debris disks around stars are currently only imaged in the sub-mm band with sufficient spatial resolution to give information on their morphology but with no information on the make up of the dust itself. Spitzer has good sensitivity in the key FIR region, but insufficient angular resolution; JWST has sufficient spatial resolution but only covers up to 27 \( \mu m \) thus missing the peak of the thermal emission and many of the important solid state spectral diagnostics. With SPICA we will not only be able to image the dust around young objects in the process of planet formation in the wavelength region where the dust spectrum peaks, but we will also be able to tell the physical nature of the material from which planetary systems form. This is because the 25-60 \( \mu m \) region has been shown to be rich in solid state features that can be used to determine both the nature of the dust and give direct access the physical conditions under which the dust/gas chemistry takes place. These features are broad and faint and therefore difficult to detect without full and uninterrupted wavelength coverage, excellent sensitivity and a spectral resolution matched to their intrinsic width. The spectrometer proposed here will allow us to characterise the nature and the location of the material within the forming planetary system for the first time, allowing us to test theories of the formation of our own solar system and other planetary systems.

A FIR spectrometer with this type of sensitivity and spatial resolution will also greatly increase our understanding of the physics and chemistry of the interstellar medium and star formation regions of our own and nearby galaxies by allowing complete coverage of the diagnostic lines that reveal the physical conditions in the ISM, star forming clouds and highly evolved stars. It is now clear that in the dense regions where, for instance, the initial phases of star and planetary formation takes place, the chemistry of the gas and dust is strongly influenced by interactions taking place on the surfaces of the dust particles. The chemical make up of the dust is a critical determinant in how this chemistry takes place and the solid state features seen in the mid to far infrared will also allow us to determine the nature of the dust.

In order to exploit the capabilities of the SPICA mission we propose that a European-based consortium can provide an imaging Fourier Transform Spectrometer (FTS) with a goal of covering the range from 25-206 \( \mu m \). This will allow us to observe the local Universe in all the FIR cooling lines characteristic of star formation and the interstellar medium, with the lower and upper wavelengths chosen to include the important H_{2} (28 \( \mu m \)) and NII (205 \( \mu m \)) lines. An imaging spectrometer is proposed to take full advantage of the potential efficiency of an FTS instrument both in taking spectra of multiple objects at high redshift and in direct spectroscopic imaging of the local Universe.

The low temperature of the SPICA telescope means that the proposed instrument is limited in sensitivity only by the detector noise for any reasonably achievable detector technology. The detectors available in this wavelength region are either photoconductors, as used on ISO, Spitzer, Astro-F and Herschel, or superconducting detectors such as Transition Edge Superconducting (TES) bolometers. The latter offer the prospect of larger and more sensitive arrays but would require some development for use in space missions; this development is already going on in Europe. There is substantial interest within Europe in the science that would be enabled by such an instrument on SPICA, and a great deal of relevant technical capability as a result of ISO and Herschel. The combination of European and Japanese expertise in the development of space-based infrared missions and instrumentation can lead to the development of a world-class astronomical facility that will revolutionise the study of the evolution of galaxies, the formation of stars and planets, and the nature of the ISM in our own and nearby galaxies.
1. Introduction

This document is a summary of the work carried out during a short conceptual study into a possible European instrument for the SPICA mission. The participants in the study include some of the leading European institutes in the field of space-borne infrared instrumentation; the individuals who have directly contributed to this report are listed here:

- RAL, U.K. Bruce Swinyard, Doug Griffin
- Cardiff University, U.K. Matt Griffin, Kate Isaak, Phil Mauskopf
- Imperial College, U.K. Dave Clements, Michael Rowan-Robertson
- University of Sussex, U.K. Seb Oliver
- University of Kent, U.K. Glenn White
- UCL, U.K. Mike Barlow
- MPE, Germany Walfried Raab, Albrecht Poglitsch
- SRON Wolfgang Wild, Thijs de Graauw, Henk Hoevers
- Leiden Observatory Paul van der Werf
- CESR France Martin Giard, Christine Joblin
- CEA SAp France Sue Madden
- Observatoire de Bordeaux France Jonathan Braine
- IAS, France Guillaume Lagache
- OAMP, France Annie Zavagno, Denis Burgarella
- ESA Estec Göran Pilbratt

With encouragement from the Japanese SPICA mission team, have made an evaluation of
- the main science goals for future FIR space observations and SPICA in particular;
- the corresponding science drivers for a far infrared spectroscopic instrument;
- the main instrument requirements as determined by the science drivers;
- options for instrument concepts (spectrometer types);
- options for the detector technology;
- key spacecraft constraints and budgets that will influence the instrument design;

We submit this proposal to ISAS/JAXA for inclusion of the FIR spectrometer concept into the SPICA payload. Assuming that the concept is acceptable to the SPICA team we will then formally bid to our funding agencies for a full Phase-A study into the instrument design to coincide with the SPICA mission Phase A study. For the purposes of this study the instrument being proposed is named ESI – the European SPICA Instrument.

We would like to thank Professor Matsumoto, Professor Shibai, Professor Nakagawa and Dr Enya for their encouragement and support over the course of this study.

2. The Scientific Case for a Far Infrared Spectrometer for SPICA

2.1 Other missions and why SPICA is important

The mid to far-infrared region (~ 5-200 µm) of the electromagnetic spectrum is an important window for studying physical and chemical processes taking place in a wide range of astronomically important objects. Access to most of the far infrared is possible only from stratospheric and satellite platforms due to absorption by the Earth’s atmosphere. Several highly successful space observatories have been flown over the years to exploit the spectroscopic opportunities in this waveband, including ISO, IRTS, and now Spitzer. Infrared space missions so far have all had cryogenically cooled apertures of less than 1 metre, and so have been limited in terms of collecting area, angular resolution, and sensitivity.

The spectroscopic instruments on board ISO have shown how powerful is the technique of FIR spectroscopy in studying the physics and chemistry of the interstellar medium in our own and other galaxies. ISO’s spectroscopic studies were limited by its sensitivity to study of the local universe: our own and relatively nearby galaxies.

Astro-F, to be launched in 2005, will carry out an all sky survey at wavelengths of 12, 20, 60, 170 µm at angular resolutions of 30 – 50 arcseconds, and sensitivities 10 - 100 times better than the IRAS survey, and will have a survey spectrometer covering 50 – 200 µm. Herschel, to be launched in 2007, will have a larger 3.5-metre aperture, passively-cooled to around 80 K, and will provide a major advance in spatial resolution and sensitivity. But its warm aperture will limit its ultimate sensitivity for photon-starved spectroscopy, and it will not cover wavelengths below 60 µm. The James Webb Space Telescope (JWST) will be launched in 2011 and will have the equivalent of a 5.8 m aperture but will only cover the wavelength range from 1 to 27 µm, thus missing the peak of the cosmic infrared background emission and all of the most important “cooling” lines in the interstellar medium of our own and other galaxies.
Astro-F and Herschel will pave the way for the SPICA mission, which will have the same size aperture as Herschel, but cooled to liquid helium temperature, and operating at wavelengths as short as 5 µm. With its cooled 3.5m diameter mirror with superb optical quality, SPICA will combine the advantages of a low thermal background with increased collecting area and superior angular resolution to achieve sensitivities of factors of between 20 – 1000 compared to Spitzer and Herschel depending on the detector technology available. SPICA will also match the sensitivity of the JWST at around 20 µm due to its lower temperature telescope, albeit with slightly lower angular resolution.

The SPICA mission, therefore, represents a major increase in sensitivity in the mid to far infrared will open up a previously unexplored region of parameter space.

2.2 Science drivers for a space-borne far infrared spectrometer

The characteristic fingerprints of star formation occur prominently at mid-infrared/far-infrared wavelengths. By their very nature, dust- and gas-rich star-forming regions are highly obscured; the dust absorbs a significant fraction of all light short-ward of the near-infrared and re-radiates this energy in the far-infrared. The gas reservoirs cool through an extensive network of atomic, ionic and molecular cooling lines, which include the fine-structure lines of carbon and oxygen, ionic lines of neon and sulphur as well as many rotational transitions of molecules such as water and carbon monoxide. The lines can be very strong, emitting many up to a percent of the total far-infrared bolometric luminosity. Through observations of combinations of lines it is possible to disentangle the complex dependencies and so to start to characterise the physical properties that parameterise star-formation such as the nature and strength of the interstellar radiation fields, chemical abundances, local physical temperatures and gas densities. These powerful diagnostics can be used to study star-formation both very locally, and in the very distant Universe. Very importantly, line ratios can be used to distinguish between hard and soft radiation fields, and so between the dominance of AGN and starburst heating processes.

We can “naturally” split the wavelength coverage of any possible instrument into three as governed by the breaks in the detector technologies and spatial sampling requirements (see later section for a discussion on this). Table 2-1 gives examples of the type of science that is possible in each band and comments on what has already been achieved – or will be achieved – by other missions.

We can see from the table, and the detailed science cases outlined below, that, on the assumption that other instruments on SPICA will cover the wavelength ranges above 200 µm and below 28 µm; the “natural” wavelength range for ESI is from 28 to 206 µm (the ground state of H₂ to the ground state of NII) and we consider this as our goal. Some reconsideration of this wavelength range may be necessary in the light of technical constraints.
### Table 2-1: Examples of scientific projects that can be advanced in the far infrared and a summary of what has/ will be achieved by other missions.

<table>
<thead>
<tr>
<th>Band (µm)</th>
<th>Science</th>
<th>Other Missions</th>
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<tr>
<td>25-50</td>
<td>This band allows sensitive studies of faint parts of the ISM looking at dust characteristics as it contains the peak of the SED for Very Small Grain emission and crystalline water ice band at ~44 µm – among other solid state features. Absorption and emission line studies along many more lines of sight to fainter background targets looking particularly at the H₂ ground state line at 28.5 µm – it is most important that the band is stretched to reach these lines. Also, this band contains water, OH and other “light hydride” lines – these are not ground state transition so interpretation is more difficult. Looking at HII regions, SNRs, PNe etc one can make a more complete survey down to much fainter limits looking at all the lines above plus the HD R(2) line at 37.7 and ionised species e.g. [SII] (33.5 µm), [SiII] (34.8 µm), [FeII], [NeIII] (36.0 µm) etc. Many key lines at wavelengths shorter than 30 µm will be redshifted into the instrument band in the case of distant galaxies - e.g., [NeII] (12.8 µm), [NeIII] (15.6 µm); [OIV] (25.9 µm). These lines have been very successfully employed to diagnose the UV field in galaxies using ISO observations – with SPICA this can be done for distant galaxies. Low-frequency modes of carbon macromolecules: such as chains, cyclic clusters and polycyclic aromatic hydrocarbons (PAHs) fall in the spectral range of SPICA. This would be a unique way to identify these molecules and monitor the carbon chemistry in various environments.</td>
<td>Band covered by ISO SWS and LWS with available detector technology (Ge:Be) which is poor compared to longer and shorter wavelengths. Sensitivity was a few x 10⁻¹⁸ W m⁻² at best. The Spitzer IRS instrument extends to 38 µm with a resolution of 600. No future mission covers this important band: Astro-F starts at 50 µm. Herschel starts at 60 µm. JWST extends only to 28 µm.</td>
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<tr>
<td>50-100</td>
<td>Going beyond 50 µm is essential to cover the [OI] ground state line at 63 µm in order to fully characterise the neutral gas environment in many different environments. For solid state features this band includes the ice band at ~62 µm and completes the picture of many of the broad faint solid state features first detected by ISO. It contains the peak of warm ISM emission at ~30 K; the [OIII] lines at 52 and 88 µm and numerous water; OH and other “light hydride” lines – if the band is stretched to 120 µm it will include the important ground state transition of OH. In addition to the ionic species in the 25-50 µm band we would see the [NIII] (57.3) line which again is an important probe of the ionised ISM less prone to extinction. In this band we start to get high J CO lines (and isotopes) which are important in pre-collapse object studies. This band contains both HD R(1) 56 and the important HD R(0) 112 ground state line. The sensitivity of SPICA will be such as to start to allow absorption line studies of HD to really probe the HD abundance in the ISM for the first time.</td>
<td>ISO-LWS line sensitivity was about ~1 x 10⁻¹⁶ W m⁻². Herschel PACS line sensitivity is estimated as ~ 5 x 10⁻¹⁸ W m⁻², and Astro-F will achieve ~1.3 x 10⁻¹⁷ W m⁻². With its much larger aperture, SPICA will be at least 25 times more sensitive.</td>
</tr>
<tr>
<td>100-200</td>
<td>The science is very much enhanced by extending to 200 µm with the addition of the [OI] (145 µm) and – especially – the ubiquitous [CII] (158 µm) line as well as more “light hydride lines” including OH ground state at 119 µm; the strong H₂O fundamental transition at 179.5 µm and a more complete coverage of the CO high-J lines giving a powerful diagnostic for pre-collapse objects. Many of the lines shortward of 100 µm will still be observable for objects of redshift 1 and above if this band is covered. Stretching the band to 206 µm will allow us to study the ground state transition of [NII] – the ratio of this line and the higher state transition at 122 µm is extremely important in the determination of the ionisation state of the ISM.</td>
<td>ISO-LWS line sensitivity was ~1 x 10⁻¹⁷ W m⁻². Herschel PACS will reach ~ 2 x 10⁻¹⁸ W m⁻² and Astro-F ~ 5 x 10⁻¹⁸ W m⁻². Again, a factor of at least 25 better will be achieved with SPICA. ISO did not reach the 205 [NII] line – Herschel will cover this line with low sensitivity.</td>
</tr>
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</table>
2.3 The Local Universe

The same spectral lines used to determine the physical conditions in local star-forming regions make powerful tools with which to study the same environments in a wide range of different types of extra-galactic source (Table 2-2). The family of mid- and far-IR lines include those from many different species, with a range of different ionisation potentials and excitation conditions (Table 2-3); used together, they therefore place constraints a wide space of physical conditions and phases of the ISM -- from the quiescent, molecular ISM, to the neutral atomic ISM and through to the ionised ISM as seen in photo-dissociation regions and HII regions. The strongest lines that fall into the 25 – 206 um window include the fine-structure transitions of singly ionised Carbon (158 µm), neutral Oxygen (63 µm/145 µm), doubly ionised Oxygen (52/88 µm) and singly ionised Nitrogen (122/205µm). In principle, by combining observations of both different elemental species and different transitions of a single species, one can determine the temperature and density of both the gas and electrons in the ISM, the strength of the local far-UV ionising radiation field and elemental abundances

<table>
<thead>
<tr>
<th>What do we need to study?</th>
<th>Why is this important?</th>
<th>Why study in the FIR?</th>
</tr>
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<tbody>
<tr>
<td>Chemical Complexity</td>
<td>Study of molecular chemistry and building blocks to large molecules</td>
<td>MIR bands not specific enough to identify individual molecules - only in FIR can we see unique identifiers</td>
</tr>
<tr>
<td>Elemental abundances</td>
<td>Study of galactic chemical evolution</td>
<td>Direct measurement of atomic lines from galactic plane and dusty, obscured nuclei possible without effects of extinction</td>
</tr>
<tr>
<td>Gas density and temperature</td>
<td>Measure of the conditions in star-forming regions in galaxies, near and far – assessment of the capacity of the ISM to form stars</td>
<td>FIR and submm wavebands are hosts to the only sensitive probes of the molecular/neutral phase – with different tracers probing different temperature/density/ionisation regimes</td>
</tr>
<tr>
<td>Far UV ionising radiation fields</td>
<td>A measure of the hardness of the UV field provides a means of distinguishing between sources in which AGN or starburst activity dominate</td>
<td>Ratios of the far-infrared emission lines of different ions of same atom provide a measure of the hardness of the UV field which is less sensitive to extinction than optical line ratios</td>
</tr>
</tbody>
</table>

Shown in Figure 2-1 is the composite FIR SED of M82 measured with the ISO spectrometers. Such observations, along with those made pre-ISO with the KAO, illustrate the importance of the rest-frame FIR cooling lines, the brightest of which can emit up to 1% of the total FIR luminosity. Very importantly, the FIR is largely unaffected by dust extinction in all but the most dense regions which means that the cooling lines can be used to probe highly obscured regions of star-formation. An excellent example of this can be seen from studies of the Antennae, the archetypal local merger comprised of the two galaxies, NGC 4038 and NGC 4039. Whilst no obvious signs of activity are visible between the two nuclei at optical wavelengths, both [CII] (Nikola et al., 1998) and CO (eg Wilson et al., 2000) emission in the FIR and sub-millimetre wavebands respectively peak in the overlap region, tracing extra-nuclear star formation triggered by the galaxy interactions (Figure 2-2). Such studies underline the significance of the FIR tracers to extragalactic astrophysics - the combined insensitivity to dust extinction, and diagnostic power means that the lines can be used to investigate the nature of the power source responsible for the prodigious far-infrared luminosity of the ultra-luminous infrared galaxy population that can often have a high level of extinction or totally obscured at optical and infrared wavelengths. The LWS on ISO (43–197µm) was used with great success to study the properties of the central regions of nearby galaxies, and the global properties of a wide selection of more distant galaxies including starburst, AGN and more quiescent galaxies. One of the most important results from ISO was the discovery that the fractional luminosity in the FIR lines depends on the bolometric luminosity of the sources themselves: Arp220 (figure 2-3) is one of the most luminous IR galaxies in the local Universe – the typically bright [CII] emission was only just detected at levels less than 1/20th of that seen in M82, with many of the other key far-infrared cooling lines seen in absorption only whereas they are in emission in M82. Gonzalez-Alfonso et al (2004) have modelled the observed spectrum of Arp220 and conclude that the nucleus is shrouded in a dense extended region of gas and dust heated by absorption in the FIR; in M82 the star burst phase does not appear to be associated with the presence of large amounts of dust and colder material. The stellar populations do not appear to be very different with similar ages of populations, and similar starburst activity throughout the galaxies. However, the greatest differences are probably due to geometry, and how the gas/dust is distributed with respect to the stars. Thus the opacity affects these otherwise similar galaxies in very different ways across the full SED coverage. Why this should be is far from certain and it is necessary to establish whether Arp220 or M82 type galaxies represent the prototype for galaxies undergoing rapid rates of star formation, and therefore an explanation for the CIRB. Understanding the difference between these types of galaxies in the local universe is also critical to understanding the role of FIR cooling lines and their use as diagnostics of the physical conditions in starburst galaxies in the distant universe. ESI will greatly enhance our understanding in this area by mapping the distribution of dust and gas in nearby
galaxies and by its ability to measure the complete FIR waveband in many more galaxies giving a much more complete survey of the zoology of the local universe.

<table>
<thead>
<tr>
<th>Line/wavelength</th>
<th>Transition</th>
<th>IP (eV)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NII]</td>
<td>121.7um</td>
<td>3P_{5/2} - 3P_{3/2}</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td>203.9um</td>
<td>3P_{3/2} - 3P_{1/2}</td>
<td></td>
</tr>
<tr>
<td>[OIII]</td>
<td>51.8um</td>
<td>3P₂ - 3P₁</td>
<td>35.1</td>
</tr>
<tr>
<td></td>
<td>88.3um</td>
<td>3P₁ - 3P₀</td>
<td></td>
</tr>
<tr>
<td>[CII]</td>
<td>157.9um</td>
<td>2P_{3/2} - 2P_{1/2}</td>
<td>11.2</td>
</tr>
<tr>
<td>[OI]</td>
<td>63.1um</td>
<td>3P₂ - 3P₁</td>
<td>IP(O → O⁺) ~ IP(H → H⁺) so emission only seen from neutral regions. Used along with CII and the FIR continuum to constrain the incident FUV flux. Ratio used to measure local temperatures around 300K.</td>
</tr>
<tr>
<td></td>
<td>145.5um</td>
<td>3P₁ - 3P₀</td>
<td></td>
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</table>
Figure 2-1: A composite spectrum of M82, taken with LWS and SWS on ISO. Note the prominent emission lines at 63 μm [OI], 88 μm [OIII] and 158um [CII], and two weaker lines of [NII](122 μm) and [OI] (145 μm). Also present are weaker molecular lines in emission – notably OH and H2O. The lines probe different phases of the ISM and, when combined, can be used to not only constrain the physical conditions in the observed region, but also to set an age to the starburst that powers the FIR emission.

Figure 2-2: A map of the integrated intensity of the [CII] line in the Antennae, superposed over an optical image (taken with the KAO by Nikola et al., 1998). Note that the [CII] emission traces a very different component from the optical, peaking in the overlap region where the optical extinction is highest. ESI will be able to map all species in the FIR range over this area in a short time due to its large field of view.

Figure 2-3: The ISO LWS spectrum of Arp220, one of the brightest local ULIRGs – the strong emission lines seen in M82 are almost completely absent but many of the same species are seen in absorption (Gonzalez-Alfonso et al 2004)
2.3.1 Elliptical Galaxies

While the precise role of elliptical galaxies in evolution models is still an open issue, nevertheless they place the tightest constraints on the formation history of the universe. One cosmology scenario has them forming early-on in the universe, leaving them as quiescent objects, evolving passively into old age. Other evidence supports the idea that they have formed from more recent galaxy-galaxy merger events and have current star formation activity. Indeed, a large fraction of nearby elliptical galaxies (up to 78%) shows fossil footprints of recent mergers, such as dust ripples/lanes in their central regions, primarily from optical obscuration (Schweitzer & Seitzer 1992; van Dokkum & Franx 1995; Goudsloof & de Jong 1995). Determination of the properties of the dust and gas in elliptical galaxies as well as their distribution relative to the stellar components, will provide important clues to the origin as well as the fate of the ISM and therefore trace the evolutionary history of the galaxies.

Elliptical galaxies are composed mostly of stars, and are very faint emitters in the MIR and FIR. Thus, initially, in our local universe we have convenient laboratories in which to study the interplay between star formation and the ISM in environments that have not experienced much repeated recycling through repeated episodes of star formation, so improving considerably on our understanding of the conditions of the primordial ISM.

Elliptical galaxies were thought to be void of ISM. Then the IRAS mission demonstrated that a large fraction (up to 50%) of early type galaxies do indeed show non-negligible dust masses (~10^{-7} – 10^{-6} M_\odot; Jura et al. 1987; Knapp et al. 1989). More recent ISO and Spitzer studies (Bregman et al. 1998; Xilouris et al. 2004; Pahre et al. 2004) confirm the presence of dust emission in the MIR to FIR regime as well as the presence of PAHs. The dust masses seem to be larger than expected given possible dust formation sources (e.g. stellar-mass loss) and the timescales for destruction (Jones et al. 1996; Jones 2004) suggest an external origin for this dust. How the dust has survived and formed the present-day structures, after being subjected to the hydrodynamical processes of the merging event, is not completely straightforward. In addition to this external source of dust, there is also the evolved stellar population as an on-going source of dust into the ISM. Such dust should be subjected to sputtering and should be depleted, upon contact with the hot (T > 10^6 K) ISM, on relatively short time scales - of the order of 10^4 yr (Jones 2004).

The hot, ionising gas properties of elliptical galaxies have been studied in X-rays, which trace their voluminous reservoir of hot (10^6 to 10^7 K) gas while the warmer, ionised, gas is traced by low-surface brightness optical emission lines where possible. The presence of cooler gas in the form of HI and CO has been a challenge to detect (e.g. Lees et al. 1991; Wiklind et al. 1995). More recently, the FIR fine structure lines of [CII] and [OI], tracing the cooler ISM, have been detected with the ISO LWS for the first time in 4 elliptical galaxies. While these and other FIR fine structure lines are valuable quantitative probes of the relatively unknown properties of the cool gas conditions in elliptical galaxies, they are have been almost completely inaccessible with ISO and will continue to be so with Herschel, due to their inherent faintness. From the few cases revealed to date by the ISO LWS, the L[CII]/L(FIR) is very low in these galaxies by a factor of up to 5 compared to other normal gas rich spiral galaxies for example. This, in conjunction with the observed low L[CII]/L(CO), speaks for a softer radiation field and low radiation field density present in ellipticals (on the order of ~10^2 G_\odot). The sensitivity of ISO CAM, was insufficient to probe the FIR gas lines at all.

Despite the improvement in sensitivity in the FIR from IRAS to ISO and now Spitzer, the ESI on SPICA will revolutionise our knowledge of the properties of the ISM in elliptical galaxies and their role in the history of galaxy evolution. A low resolution FIR to FSED survey of elliptical galaxies, not possible before SPICA, will permit detailed dust modelling to determine the properties of the various dust components as well as the valuable knowledge of their spatial variations. Having the capability to characterise the cooler gas, through the FIR fine structure lines as well as the wide variety of ionised FIR lines will be the beginning of an unprecedented era for elliptical galaxy studies.

This will finally open the door to discussion concerning the origins and evolution of the dust in elliptical galaxies.

2.3.2 Low metallicity Dwarf galaxies:

In our local universe we have convenient laboratories in which to study the interplay between star formation and the ISM in environments that are reminiscent of conditions in the early universe. We have recently seen that the spectral features of the dust and gas content of low metallicity starburst galaxies in our local universe differ remarkably from those of the gas rich starburst galaxies (Galliano et al. 2003, 2004; Madden et al. 2004). A wide variety of new, moderate-to-very low metallicity dwarf galaxies, with metallicities as low as 1/50th solar, have recently been detected in deep optical surveys (Ugrumov et al. 2003). Herschel-PACS will be the first instrument to begin to explore the FIR fine-structure cooling lines in these galaxies, however it will not be able to do much beyond the [CII] and [OI] lines in many of these galaxies of extremely low metallicity, due to their intrinsically faint nature and the fact that the instrument sensitivity is limited by the warm Herschel telescope. For example, obtaining both 122 um and 205 um lines of [NII] and the 57 µm lines of [NIII] will be prohibitive with PACS for most of the dwarf galaxies. The [NII] and [NIII] lines, along with the [OIII] 88 µm lines would enable the N and O abundances to be derived for the ionized gas components. Thus, it will be up to ESI on SPICA to delve into the treasure trove of these dwarf galaxies surveys and characterise the ISM under conditions that have not experienced much repeated recycling through repeated episodes of star formation, so improving considerably on our understanding of the conditions of the primordial ISM.
2.3.3 Extended gas component in galaxies

Whilst considerable progress has been made in the last few years in identifying the origin of the extra-galactic FIR background, a significant fraction cannot be resolved by the submm-bright sources first detected by SCUBA. More than 50% of the FIR is likely made up of emission from other classes of object, such as, for example, more quiescent spiral galaxies. When mapped in the most important FIR cooling line of [CII], for example, it is apparent that the integrated flux of the low surface brightness, diffuse and extended gas component of spiral galaxies that makes the largest contribution to the integrated output from the whole galaxy, and not the nuclear component. It is therefore important to establish the physical conditions across a wide range of different phases of the ISM in local, resolved, galaxies before we can interpret accurately the ISM properties of the huge numbers of unresolved sources that will be uncovered by Herschel and other deep FIR and submm surveys. The ISOLWS made considerable progress towards achieving this in spite of having no imaging capability (Contursi et al 2002; Negishi et al 2001). PACS will build on this work, however even it will have extreme difficulty in mapping the extended and low surface brightness component of galaxies, due to the lack of sufficiently accurate reference observations inherent to the warm telescope. Thus, the ESI on SPICA will be the first instrument able to study this component in detail by mapping the wide variety of FIR diagnostic cooling-lines across an extensive range of different galaxy types.

2.4 The high-redshift Universe

One of the primary goals of modern astrophysics is to gain a detailed understanding of the formation and evolution of galaxies. It is known that nearly half of the stars we see in the present Universe have formed since the \( z=1 \) epoch, it is far from clear when or how the galaxies in which the highest star formation rate occurred, and is still occurring, formed. Combined with this, one of the most important astronomical results of recent years has been the discovery of a previously unknown population of distant galaxies that emit a significant fraction of their enormous total bolometric luminosity in the rest-frame FIR \( (L_{\text{FIR}} > 10^{11} - 10^{12} L_{\odot}) \). These galaxies account for 15 - 20% of the total, integrated FIR luminosity, and so are of considerable cosmological significance. The inferred presence of prodigious quantities of dust and molecular gas suggests that these galaxies are very young, and probably caught undergoing one of their definitive bursts of star-formation. A similarly FIR-luminous phase has been identified in the host galaxies of high-redshift AGN, suggesting that there is a causal link between massive starbursts and black-hole growth and formation. Characterising and quantifying the roles of different physical processes taking place in these very dusty galaxies is therefore central to placing this FIR-luminous phase onto the evolutionary timeline of galaxies. The same dust that emits so strongly in the rest-frame FIR results in high visual extinction in these objects: studies of only the most luminous of this population are possible at optical and near-IR wavelengths. The high visual extinction means that the mid/far-infrared cooling lines and PAH features are key probes with which to address a number of very basic questions – table 2-4 lays out these questions, why we should address them using the FIR and how ESI will address them with its unique combination of wavelength coverage and sensitivity. The rest of this section discusses the detail of the scientific projects behind each of these questions.

| Table 2-4: Fundamental questions in extragalactic science addressed by ESI |
|---------------------------------|---------------------------------|---------------------------------|
| Question                        | Why study in the FIR?           | What is unique about ESI        |
| How and when were “normal”      | As for local Universe important | The combination of spectral      |
| galaxies assembled between z=1  | diagnostic lines do not suffer  | coverage and sensitivity allows  |
| and the present epoch?          | extinction FIR lines give unique, model independent, information on chemical evolution |
|                                 |                                 | detection of normal galaxies to z=1 and allows access to all common atomic species. Spectral resolution gives ability to break the confusion limit imposed by the telescope aperture. |
| What is the nature of the power | FIR gives access to atomic and   | Wavelength coverage to give full access to all lines and redshifts. The ESI sensitivity allows us to look out to much higher redshifts for the first time. |
| source behind the high-redshift| ionic fine structure lines without needing to correct for dust extinction. Most especially the MIR ionic lines of Ne,S,Si and O are redshifted into the FIR beyond \( z=2 \). |
| FIR galaxy population?          |                                 |                                 |
| Do all “normal” galaxies have a | Measurement and characterisation of the UV field by looking for ionic lines present or redshifted into the FIR. Simultaneous characterisation of star formation rate from SED. | Wavelength coverage to give full access to all lines and redshifts. Sensitivity allows us to look out to much higher redshifts for the first time. With the low resolution mode of ESI we can accurately measure the SED. |
How does the luminous FIR population compare to its local analogues?  
Survey of local and distant galaxy populations looking at the same species only possible in the FIR.  
Sensitivity and wavelength coverage allows ESI to detect fainter local galaxies and with the same instrument survey to higher redshifts using spectral resolution to break spatial confusion limit.

How does star-formation vary with local environment and cosmological epoch?  
The same diagnostics can be applied to both isolated galaxies and clusters of galaxies.  
The imaging spectroscopy ability of ESI will allow rapid observation of clusters of galaxies with high sensitivity.

2.4.1 FIR and MIR Spectroscopic studies of the high-redshift Universe
Observations of the type that will be made using Herschel-SPIRE and Herschel-PACS instruments will detect numerous new sources from deep field mapping. Herschel will make some headway towards establishing the nature of the high-redshift FIR luminous population by starting to constrain the rest-frame FIR SEDs and by providing a measure of the mass and temperature of the copious amounts of dust typically found in these objects. It is, however, only with the complementary range of diagnostic tools provided by narrow-band spectroscopy that it will be possible to determine the physical conditions of the gas within these distant sources, characterising the star formation properties of these galaxies and thus establishing the true nature of the far-infrared luminous population. PACS and SPIRE on Herschel will have sufficient sensitivity to only investigate the gas properties of the very brightest of the distant, FIR-bright population. ALMA will provide an opportunity to study the molecular ISM through observations of redshifted CO, HCN and other ubiquitous molecular species, however to gain a complete picture of the energy balance in the ISM requires spectroscopic studies in the FIR. The same, far-infrared fine-structure lines used to study the ISM in local galaxies will be detectable out to redshifts of $z \geq 2$ with an ESI – indeed, it should be possible to detect not only the most exotic and extreme examples of far-infrared-luminous galaxies, but also those more typical of the population as a whole. Shown in Figure 2-4 is a plot of the emission from an M82-like object, but with a more typical total luminosity, redshifted to a selection of cosmological redshifts – if one makes the simplifying assumption that the fractional line luminosities of a high-redshift FIR-luminous source are comparable to those measured in M82 (known not to be the case for Arp220 see above), then objects that are more than a factor of 5-10 brighter than M82 will be detected in a number of the key redshifted MIR and FIR lines out to a redshift of at least 2.5 – see section 4.

2.4.2 Galactic evolution: observations of intermediate redshift galaxies
The Cold Dark Matter cosmology which has now survived many observational tests with success predicts that the first galaxies were quite small and that galaxies have reached their current size and morphology through a succession of merging events. Observations of intermediate and high-redshift sources have shown that the comoving star formation rate density in the universe was at least a factor 10 higher at a redshift of unity (Madau et al 1996, Hughes et al 1998, Heavens et al 2004...), such that half or more of the stars in the universe have formed since $z \sim 1$. Moreover, they have also shown that much of this star formation is dust obscured, so that UV and optical observations are incapable of providing a true census of star formation without resorting to large, and uncertain, obscuration corrections. With SPICA ESI, operating around the peak of the far-IR SED, we can, for the first time, follow the evolution as a function of redshift of galaxies that become spiral galaxies like our own using both the unique diagnostic lines available in the 25-200 $\mu$m range and the ability to accurately measure the dust emission.

In figure 2-4, we show the spectrum of a galaxy which is very similar to our own over the range from 10 GHz to 10 THz (30 $\mu$m to 30 mm). The data come from a mixture of sources but the FIR part of the spectrum was from a long integration with the ISO LWS (Braine & Hughes 1999), detecting the [CII], [OI](63), [NII](122), [OIII](88), and possibly [OI](145) lines. We have redshifted the source to 0.2, 0.4, 0.6, 0.8, and 1 and the result is shown using the intensity scale expressed in mJy. It can be readily seen that an ordinary spiral galaxy like our own can be detected in continuum out to high redshift ($z \sim 1$) by SPICA ESI in less than an hour. More importantly, it is clear that the FIR lines measured in ordinary local galaxies can be detected out to redshifts where the universal SFR has increased by close to an order of magnitude. With ESI, we be able to establish whether current galaxies grew by collisions and merging of smaller objects over the last 8Gyr (as suggested by CDM cosmology) or whether by redshift unity the galaxies were already large and massive and more gas-rich with a higher SFR. In the latter case, the luminosities in the FIR lines and continuum will be greater than shown in figure 2-4 and the galaxies will be detected more quickly. The ESI band is ideally suited to explore the intermediate redshift range ($0.1 < z < 1$) as the FIR continuum maximum at about 120 $\mu$m for a normal spiral remains within the band out to a redshift of 0.7 and probably even further given the expected increase in dust temperature. This enables us to measure the dust temperature and how it changes with a single instrument throughout this whole redshift range. The high frequency end of the band will allow us to detect any increase in the amount of warm dust emission.
Earlier instruments have chiefly aimed at detecting starbursts such as M 82 or the Ultra-luminous IR galaxies such as Arp 220 at intermediate or high redshifts. However, such objects only make up a small fraction of galaxies. Here we propose to be able to detect a large fraction of the galaxies in the universe rather than just the brightest in order to determine how galaxies like our own have evolved. If the SFR in galaxies has increased as much as the universal SFR density, then we will even be able to detect small objects such as the Large Magellanic Cloud or M33 at redshifts to 0.5 or possibly further.

The detection of a number of major FIR cooling lines allows us to study the evolution of the physical conditions of the star forming ISM in galaxies over half the age of the universe. The synergy with ALMA is ideal as ALMA starts observing the lines roughly when they leave the ESI band. Furthermore, while ALMA will be very sensitive and detect CO and possibly CI emission over this redshift range, ESI may turn out to be more sensitive when it comes to detecting the smaller galaxies which typically have lower metallicities and highly reduced CO emission compared to their gas mass. The FIR lines seem to remain strong despite the sub solar metallicity (Higdon et al 2003).

If we are to go beyond the detection stage, it is important for ESI to reach a spectral resolution of about R=10000 (30 km/s). This would enable us to roughly measure the masses of the objects observed using their line width and the Tully-Fisher relation or the line width coupled with a real size measurement. Small objects have narrower lines and we will detect galaxies such as M33 or the LMC, or even our own if close to face-on, much more easily if a high (R=10000) spectral resolution mode is available.

Figure 2-4: Spectrum of NGC 4414, a galaxy similar to our own in terms of luminosity and dust temperature. The lines and the line ratios can be compared to those in Figures 2-1 and 2-2 to see the obvious differences with M82 and Arp220. The coloured lines are the same spectrum redshifted as indicated and the intensity for the redshifted spectra is given in mJy (Jy for the galaxy as observed). The intensities are given for a line width of 300 km/s (R=1000); at higher spectral resolution the same object would reach a higher peak intensity. These fluxes should be compared to the predicted SED mode sensitivities in section 4.3 of about 30 µJy for the nominal instrument and 3 µJy for the goal instrument. See section 4.3 for line sensitivities.

2.4.3 PAHs: Starburst or AGN?

The MIR also plays host to a number of features that are sensitive to the intensity and hardness of the local UV field, and so can be used to investigate the relative contributions from AGN and starbursts in distant sources. The most prominent features of mid-IR spectra are the emission bands of (Polyaromatic Hydrocarbons) PAHs at 6.2, 7.7, 8.6 and 11.3µm. There is also a broad absorption band centred at 9.7 um which is attributed to amorphous silicate dust; and an underlying continuum exhibiting a variety of shapes which is attributed either to transiently heated very small dust or equilibrium emission from very hot dust. PAH molecules are excited by absorption of single UV photons; consequently, and in contrast to emission from larger grains, their output does not depend on their distribution around the heating source and they are relatively insensitive to radiation from the older stellar population. This makes them good tracers of the UV field and so of star formation. The correlation between star formation and PAH emission is now well established, suggesting that up to ~10% of the FIR luminosity in external galaxies is emitted in the PAH features. At high UV field densities, such as those found close to the centre of HII regions, the underlying continuum becomes more prominent and the PAH features are depressed. At even higher field densities and/or in presence of soft X-rays (conditions found in the vicinity of an AGN) the PAH features disappear completely. In addition, and crucially for
discriminating between a star burst/AGN heating source, the slope of continuum at 8μm changes dramatically -- it is significantly smaller for AGN sources implying, as expected, high dust temperatures.

The diagnostic powers of the PAHs bands in estimating the IR flux associated with the star formation have been demonstrated by Soifer et al (2002) for M82 and by Peeters et al (2004) for normal and starburst galaxies. In addition, the ratio of the PAH bands has been shown to be a useful indicator of the ISM activity for a wide variety of galaxies (Galliano et al 2005). Whilst the IRS on Spitzer will make considerable inroad into assessing the diagnostic power of PAHs in the local Universe, it only just has sufficient sensitivity to detect PAH emission from the brightest FIR sources at redshifts of z~1 (e.g. Higdon et al, 2004 and fig 2-6): the ESI on SPICA will be able readily detect the lines at the longest wavelengths to redshifts well beyond this (see figure 2-5).

![Effects of redshift on the MIR/FIR spectrum of M82](image)

**Figure 2-5**: The combined ISO SWS and LWS spectra of a starburst galaxy with 10x the luminosity of M82 as seen at various redshifts. These spectra should be compared to the SED mode sensitivity limits of ESI discussed in section 4.3 of about 30 μJy for the nominal instrument and 3 μJy for the goal instrument. The wavelength coverage of ESI is shown by the horizontal line.

**Figure 2-6**: A Spitzer IRS spectrum of CFRS 14.1157 (z~1.0, Higdon et al 2004). The spectrum is dominated by emission from an AGN, with none of the strong PAH features characteristic of starburst that are seen in M82. At redshifts of z~2 and greater, the PAH features will start to move into the ESI band and objects of this luminosity class (~100 x M82) will easily be detected.

### 2.4.4 Molecular Hydrogen

The lowest rotational transitions of molecular hydrogen are found at 28, 17, 12.3 and 9.7 μm. These transitions provide a means by which to measure all H2 in galaxies that is at temperatures of greater than 80K (in the J>=2 levels). ISO-SWS has demonstrated the power of the MIR molecular H2 lines in locating large amounts of warm H2 from starburst galaxies and Seyferts, as well as late-type non-starbursting galaxies (e.g. Valentijn et al 1996; Rigopoulou et al 2002; Valentijn & van der Werf 1999). Some of the results may suggest the existence of previously undetected components of warm (~80 to 150K) H2 distributed throughout the cold interstellar medium for which UV photons are not necessarily the sole heating source. The IRS on SPITZER, and MIRI on JWST*, will improve significantly upon the pioneering work of ISO in this area for a wide variety of galaxies in the local universe including low metallicity galaxies, for which proxy probes of the molecular hydrogen content are unavailable. Through modelling, the MIR H2 lines should provide mass constraints on baryonic dark matter in the form of H2 in different galaxy types.

With the sensitivity of ESI on SPICA, the H2 lines can be detected in the distant galaxies, with the most favoured being the lowest purely rotational quadrupole transitions S(0): J=2-0 at 28 μm and S(1) J=3-1 at 17 μm. Whilst these MIR lines do not probe directly the cold gas (T< ~50K), the warm gas traced is expected to be intimately related to the bulk of the H2 mass, including that unrelated to star formation. With accurate mass measures of the molecular gas mass, it will be possible for the first time to obtain a first global view of the processes that control star formation.

* In JWST-MIRI the sensitivity to the 28.2 μm line is critically dependent on the exact implementation of the detectors – the quantum efficiency of Si:As is at best a few percent at 28.2 μm.
SPICA also offers the first possibility of detecting molecular hydrogen cooling lines from the precursors of the very first stars as they condensed from clumps of hydrogen and helium gas produced in the big bang. These clumps must have cooled by emission of H$_2$ the same emission lines that we see in the rest of Universe. The first objects are predicted to have formed at around $z\sim 20$ so the MIR lines will be redshifted into the ESI bands. This is likely to be the only means by which we can observe the initial formation of the very first stars. The after-effects of the first generation of supernovae may also be revealed by the formation of large amounts of H$_2$ gas in shocks and by the ejection of metals – both amenable to direct detection by far infrared spectroscopy. Whether these features will be observable by SPICA will depend on having enough objects within a single field of view.

2.4.5 Blank-sky Spectral Lines Surveys

The depths to which one can usefully undertake FIR surveys are currently set by the diameter of the telescope and the confusion limit, rather than limitations in detector sensitivity. In the absence of a larger mirror, it is possible to beat the confusion limit by adding a third dimension to the deep surveys - wavelength - and so searching for traces of star-formation using the redshifted far-infrared cooling lines directly, rather than the broad-band signatures of warm dust. As one goes from R~3 to R~100s, the line-to-continuum ratios increase markedly, and it becomes possible to distinguish the FIR line emission against the continuum. Very simple simulations suggest that it should be possible to start to resolve the far-infrared/submillimetre background through wide-area line searches, determining both the redshifts and physical properties of sources that would otherwise be impossible to differentiate between in broad-band photometric maps. The power of increased spectral resolution can be seen in Figure 2-7, where the results of some simple simulated observations (beam ~ 6") of the same patch of sky made at different spectral resolutions are shown – panel (a) simulation at R~3 centred at 70 µm no distinct sources can be distinguished above the background - any strong FIR lines present are diluted by the large bandwidth; (b) and (c) at R~1000, centred at 63.2 and 58.3 um: the effects of line dilution are considerably reduced, and a number of different sources are unambiguously detected above the background limit. The broad spectral coverage that would be achieved by the proposed ESI on SPICA would enable both the redshifts and the physical properties of these sources to be measured.

![Figure 2-7](image_url)

Figure 2-7: Simulations of blank line surveys using spectroscopy to remove spatial confusion – see text for details

There is also a middle way, between broad band photometry and spectral line searches, which will also be possible with ESI. This will be a low resolution spectroscopy mode, with resolution of about 20, which will allow the mid-to-far-IR SED of objects to be rapidly measured. This may allow redshifts and galaxy classifications of sources to be measured in a short integration time with reasonable accuracy using 'photometric redshift' techniques to fit template spectra and redshifts to these low-resolution SED observations. Such techniques have had considerable success in the optical, near-IR and Spitzer wavelength bands, and models suggest that a similar approach will be workable in the far-IR (Aretxaga et al., 2003). A low resolution 'data cube', similar to the full resolution data cubes discussed above, would also benefit from reduced effects from confusion.
2.5 The Galaxy

The Spitzer, Astro-F and Herschel missions will enormously advance our knowledge and understanding of the physical conditions and processes within our own galaxy. SPICA, and more specifically ESI will add considerably to the wealth of data that these missions because of the coupling of the high spatial resolution, and the cooled aperture, allowing us to probe faint compact structures that will dominate star formation and planet assembly regions. The wide wavelength coverage, sensitivity, spatial resolution and large field of view afforded uniquely by SPICA, and in particular ESI, will allow us to sample the faint and diffuse fine structure and molecular lines in star forming regions that are very close to us. In this section we discuss how ESI will advance our knowledge by:

- Spatially resolving the galactic cirrus further and spectrally analysing the cirrus down to the very faintest levels over large areas
- Making complete surveys of star formation regions over the complete range of mass scales and in areas of high extinction and cirrus confusion
- Detecting the diagnostic lines of PAHs in the far infrared for the first time and allowing study of the chemical complexity of the ISM for the first time
- Studies of the water and H₂ lines across all phases of star formation and planet assembly
- Following star formation over all phases of evolution and imaging the faintest parts outflow regions and evolved objects in both continuum and the critical FIR cooling lines

2.5.1 Galactic Cirrus and complete surveys of star formation regions

Galactic emission in the far-infrared (IR) sky affects the detection of faint sources. The amount of emission manifests itself as photon noise whose fluctuations follow Poisson statistics. In addition, any brightness fluctuation at scales below the beam size could cause confusion with real point sources. Emission from irregular clouds of interstellar dust on all spatial scales, commonly referred to as infrared cirrus, was discovered by the Infrared Astronomy Satellite (IRAS) (Low et al. 1984). Fluctuations in the brightness of the background radiation can lead to confusion with real point sources. Such background emission confusion will be important for infrared observations with relatively large beam sizes since the amount of fluctuation tends to increase with angular scale. The background emission due to the galactic cirrus on the detection of point sources for current and future far-infrared observations by space-borne missions such as Spitzer, ASTRO-F, Herschel and SPICA, is simulated in Figure 2-8 and the detection limits due to cirrus confusion at the short (28 µm) and long (160 µm) wavelength limits of a SPICA instrument are shown in figure 2-9. Here we have not included the additional confusion noise due to external galaxies which will become important in fainter regions of the galaxy (Dole, Lagache Puget, 2003) – the confusion limit in these regions will be similar to the case of observing blank extragalactic fields. In these regions the inherent spectral discrimination of ESI will be a powerful tool for separating galactic sources from external galaxies and for determining the correct associations between continuum and line emitting structures. In summary SPICA, and most especially ESI, will have a combination of spatial resolution, wavelength coverage and sensitivity that will allow us to understand the cirrus components and thus make unconfused, and therefore unbiased, observations of star formation regions over all mass scales in all parts of the Galaxy.
Figure 2-8: Simulated images of galactic cirrus (no external galaxies are included here) including point sources at 160 µm for ISO (upper-left), ASTRO-F (upper-right), Spitzer (lower-left), and SPICA (lower-right) missions. The mean brightness of the cirrus background is 2 MJy sr⁻¹ at 160 µm. (Jeong et al 2004).

Figure 2-9: Detection limits due to the Galactic cirrus (only) as a function of Galactic latitude. The two lines plotted for each mission are for 50 µm (lower line) and 160 µm (upper line). With its unique combination of wavelength coverage, high sensitivity and spatial resolution SPICA can peer through the Galactic murk for the first time.

2.5.2 ISM Ecology and Molecular Complexity
As discussed above, the spectral range covered by ESI dominated is by the emission of interstellar dust. These dust particles play a wide-ranging role in the physics and chemistry of the interstellar medium; they account for the interstellar extinction, heat the interstellar gas, and are suspected to play a major role in the formation of molecules, gas depletions, chemistry, ionization degree and coupling with the magnetic field. However, the impact of dust particles on the ISM ecology (chemical and physical state) is still largely unexplored due to the intrinsic difficulties in determining the make up and physical conditions of the dust. ESI will have a unique combination of large field of view, flexible spectral resolution, sensitivity and wavelength coverage that will offer the opportunity to study interstellar dust in a wide range of regions from the most diffuse clouds to the sites of star formation and protostars, and will allow us to perform photometric and spectroscopic observations in the faintest regions of the sky.
It has long been known that more complex molecules exist in all phases of the ISM, these have been detected in the MIR (PAH bands – see also section 2.4.3) and in the sub-mm and radio. The detailed identification of the PAHs remains difficult however as the emission and absorption features seen in the MIR are not uniquely diagnostic of the precise molecules from which they arise. However, the PAHs that have been proposed as the carriers of the aromatic infrared bands (AIBs) between 3.3 and 16.4 µm, have modes at longer wavelengths and sensitive spectral observations of the ISM in the FIR range are well suited to the identification of carbon macromolecules. The FIR modes are much more specific of the molecule identity than the mid-IR ones as, for instance, the floppy modes in the FIR involve motions of the whole carbon skeleton. Although they are known to exist from laboratory studies, detecting these modes in space presents some challenges:

- The fraction of the energy emitted in such a band is typically 0.1% of the energy absorbed in the UV (Joblin et al. 2002).
- The predicted width of the Q-branch of a molecule such as C_{24}H_{12} is of the order of 0.1-0.2 µm although it could be broader, depending on anharmonic effects.
- To detect such a band the limiting factor is the huge dust continuum emission and a signal-to-noise of at least one hundred is desirable to put any constraint on the PAH population.

Other molecules of interest are C_n and HC_nH species, which have no dipole moment and cannot be detected by radio telescopes. For instance, an emission band at 98 µm was observed by ISO LWS in the spectrum of NGC 7027 and attributed to C_5 (or C_6) by Goicoechea et al. (2004). Emission models have however still to be built for these larger species.

To stand any chance of detecting these transitions and really obtain important clues for our understanding of how molecular complexity can be built - we need to be able to use highly sensitive broad band spectroscopy with a flexible spectral resolution to match the, as yet unknown, width of the features. The ESI concept is ideally suited to finding these transitions as it will have both the ability to detect narrow lines and the continuum with high photometric accuracy and thus separate faint broad features from the underlying continuum.

### 2.5.3 Star formation

Star formation research has traditionally been a domain of infrared and (sub)mm astronomy. All young stellar objects emit mainly in the mid and far-infrared spectral region: protoclusters, Class 0, I, and optically visible Class II sources have peaks of their SED in the SPICA range. Figure 2-10a gives examples of the emerging protostars as seen in the mid-infrared with ISO and figure 10b shows the entire SED of a typical protostar. The spatial scale of nearby star forming regions ranges from several arcmin for cores to several degrees for entire complexes. Dust emission in protostellar objects, young stars, and star forming regions covers a wide range of dust temperatures extending from ~15 K for pre-stellar cores to ~ 80K for Herbig AeBe stars with corresponding SED peaks at ~ 200 and 60 µm, respectively. For photometry of typical objects likely to be detected in surveys, it will be essential to include these wavelengths. The high spatial resolution possible at shorter wavelengths is also needed to establish structure and temperature profiles of pre-stellar clumps.

The processes by which stars, protoplanetary disks and planets are formed remains poorly understood. The high spatial resolution of SPICA is needed to resolve protostellar disk formation, to image gaps in disks around more mature pre-main sequence stars and to detect faint brown dwarfs and extrasolar giant planets close to their bright parent stars. Because star- and planet formation is accompanied by huge changes in the physical conditions, with densities ranging 10^3 to 10^{13} cm^{-3} and temperatures from 10 to 10,000 K, there are a wealth of atomic and molecular lines available with which to unravel the physical structure and evolution. Moreover, these lines can be used to trace the chemical composition of gas and dust through the various stages of the star formation process, thus providing an inventory of the building blocks available for new solar systems.
2.5.4 Young stars

Radiation and outflows from young stars excite the surrounding interstellar medium. Spectroscopy of the envelopes of young stars and the interstellar medium in both star forming regions and more diffuse environments is the key tool to study the interaction between the forming star and the surrounding cloud. Mid and Far infrared observations with SPICA will be particularly powerful to provide insight into the physical processes occurring in the deeply embedded proto-stellar phase when the star is still being assembled through accretion of material from the circumstellar disk. The fragmentation of the collapsing cloud into binary or multiple star systems and the formation of the disk itself are key questions, which can likely only be addressed properly through combined JWST near-infrared, SPICA far-infrared and ALMA sub-mm data. Infrared continuum images at $>20\,\mu m$ probe the warm part of the accretion disk and the inner envelope, constraining the geometry and the elusive mass infall rate. Imaging in different spectral features such as the $H_2$ pure rotational lines and FIR cooling lines probe the physics of the accretion shock at the disk surface, as well as the interaction of the outflow with the inner envelope as it starts to clear the surroundings. Periodic structures in the outflow jets may be used to trace the recent accretion history of the central proto-star. The PAH features track the importance of ultraviolet radiation in dispersing the envelope. Together, such data can trace the proto-stellar evolution from the earliest collapse to the phase where the young stars emerge from their natal cocoons. A wide range of molecular (CO, OH, HD, H$_2$O, etc.), atomic and ionic species is observable in the SPICA wavelength range. In many cases analysis of photodissociated or shocked regions is involved, for which the [O I] 63\,\mu m line is crucial. At the long end, the [N II] 205\,\mu m transition provides a diagnostic of the ionized medium. Studies of the SED using low resolution spectro-photometry has been shown to be a powerful tool in the classification of protostellar objects (figure 2-11) such as will be detected in surveys carried out by Astro-F and Herschel. ESI will have the sensitivity and flexibility in spectral resolution to correctly characterise the evolutionary phase of these objects.
High-mass stars are the key ingredients in determining the evolution and the energy budget of a galaxy at all redshifts. Yet our understanding of how a massive star forms is surprisingly poor with respect to solar-mass regimes, mainly due to the poor spatial resolution of the facilities currently available to study these relatively distant objects from the infrared to the radio wavelengths. Since more massive stars are indeed observed in our Galaxy, several mechanisms have been proposed to understand their formation. In principle, more massive stars could also be built via an accretion process, but the mass accretion rates must be at least three orders of magnitude larger than those expected for low mass stars and most of the accretion has to be channelled through a thick accretion disk (Yorke 2003). The strong link observed between the formation of massive stars and the formation of dense stellar clusters suggests alternative scenarios involving dynamical evolution in clusters. In this view, during the early evolution of clusters competitive accretion favoured the formation of the more massive objects close to the cluster centre, where the (proto)stellar density is higher. Subsequent elastic collisions in these inner regions of the cluster may allow formation of one or more very massive stars as the result of merging of lower mass objects (Bonnell et al Stahler et al. 2000.). Since this latter mechanism would occur in the deeply embedded phase, only sensitive high spatial resolution observations in the mid to far infrared, combined with ALMA data, will be able to resolve such clusters of ~10–100 low-mass stars crammed into a ~1000 AU region out to a few kpc.

Key gaseous tracers of this early phase include the molecular hydrogen (H$_2$) line at 28 microns, and a forest of molecular transitions excited in warm gas. An example of this is shown in the outflow source L1448 (figure 2-12). The SPICA ESI will have the sensitivity need to measure the very faint H$_2$ lines, not only in the centres of star forming regions, but also extending outward into the more diffuse surroundings, providing an unique tracer of the thermal structure in the gas. The water lines, which are known to trace the warm and sometimes shocked environment around protostars, will be accessible to the ESI, where the combination of wide spectral range, the cooled aperture and the small beam will provide an unrivalled probe of the early development of conditions in a large sample of these regions, that should exceed the capabilities of either Herschel or JWST.
2.6 Planetary Formation

Planets form in the dense gas and dust disks that surround newly formed stars. Initially the disks are rich in both gas and dust, the gas rich phase appears, however, to be rather short lasting no more than a few Myr. The gas-rich disks seen around pre-main sequence T Tauri and Herbig Ae stars with ages of a few Myr have gas + dust masses of 0.01 $M_\text{Sun}$, similar to that of our primitive solar nebula. Once accretion onto the star stops and the dust starts to coagulate, both the geometry and composition of the disk undergo substantial changes. These changes can be studied best in the mid to far infrared spectral region, since at these wavelengths the inner disk, where planet formation is expected to occur, dominates the spectrum. In particular, changes in dust scale height affect the strength of the infrared flux emerging from the disk, while structural modifications in the dust grains result in mineral formation traced by mid to far infrared spectra. The possibility of obtaining spatially resolved images with ESI and ALMA down to $\sim 10$ AU will allow not only the dust settling, but also the relative settling of the dust versus the gas in gas-rich disks to be determined and the earliest stages of planetesimal formation to be followed up to roughly millimeter sizes. Indirect evidence for planet formation will be provided by observations of gaps in disks, where an unseen giant planet has cleared out a ring of material.

2.6.1 Gas in Circumstellar Disks

Most disks have been studied through their dust emission, but 99% of the mass is in H$_2$ gas. Not only does this gas affect the dynamics of the dust, but it is also the principal ingredient for giant Jovian planet formation. It has recently become clear that CO is not a good tracer of the gas in disks due to the combined effects of photodissociation in the surface layers and freeze out in the cold midplane (van Zadelhoff et al. 2001, Aikawa et al. 2001). In contrast, H$_2$ traces the bulk of the warm gas at T > 50 K directly. The ISO-SWS provided the first opportunity to search for the principal H$_2$ J = 2–0 S(0) and 3–1 S(1) lines at 28 and 17 $\mu$m, and detected lines not only from disks around young pre-main sequence stars (Thi et al. 1999), but also tentatively from disks around 10–20 Myr old stars such as Beta Pictoris. This would indicate that these latter objects are better thought of as the final stages of gas-rich accretion disks. The time scale over which this gas clearing occurs and the mechanisms by which it operates are critical to both planetary formation and migration models. Currently there is still no consensus whether giant planets originate through the formation of a rock-ice core followed by gravitational gas accretion or by instabilities in the outer disk and fragmentation. Combined spatially resolved observations with SPICA of both the dust and the 28.2 $\mu$m H$_2$ line as functions of age over the 1–100 Myr range will be powerful tools to distinguish between these models. These observations will only be possible with SPICA in a wavelength range where the sensitivity of JWST is falling dramatically, at the same time as the JWST thermal background is increasing sharply. SPICA will be sensitive to gas with masses of $10^{-5}$–$10^{-7}$ $M_\text{Sun}$ at $T_{\text{gas}} = 50$–200 K. High spectral (R ~ 3000) and spatial resolution is essential for this project: even though Spitzer will attempt to observe H$_2$ from disks, the low line/continuum ratio at the spectral resolution of the Spitzer IRS (R = 600) will prevent detection in most cases.

2.6.2 Debris Disks

Debris disks are produced as by-products of collisions between asteroid-like bodies and the activity of comets left over from the planet formation process. They are almost the final stage of the circumstellar disk evolution process, i.e., they are the evolutionary products of ongoing or completed planet formation. In the case of our solar system, the debris of Jupiter-family short-period comets and colliding asteroids represents the dominant source of zodiacal dust located inside the Jupiter orbit and the Kuiper Belt Objects the remnants of the material of the primordial Solar proto-planetary
In order to further study the physical conditions of star and planetary formation within our own galaxy it will be necessary to realise a combination of ever higher spatial resolution and sensitivity in the far infrared band. The necessity for this, and the need for wide wavelength coverage, is illustrated by the study of debris disks around nearby stars.

Debris disks are expected to harbour particles ranging from submicron-sized grains to planetesimals/planets (e.g., Beckwith et al. 2000). This view is consistent with observations of main-sequence and pre-main-sequence (post-Herbig Ae/Be, post-T Tauri) stars that show the distribution to extend from below 1 µm to at least about 1 mm (e.g., Skinner et al. 1992; Sylvester et al. 1996; Sylvester and Skinner 1996; Li and Greenberg 1998). Larger grains can stay in bound orbits around the star, whereas smaller ones are placed by stronger radiation pressure in hyperbolic orbits. A boundary between the two populations can be estimated from the ratio of the radiation pressure to gravity (Burns et al. 1979) and lies typically between ~ 1 and 10 µm, depending mainly on the mass and luminosity of the star and optical properties of grains. Current near-infrared surveys for excess emission indicate that the massive disks disappear on timescales from a few Myr (Haisch et al. 2001) up to ~ 100 MYrs. However, these data are only sensitive to very warm dust close to the star. Longer wavelength observations are needed to trace the evolution of the bulk of the dust beyond the classical T Tauri stage. The Spitzer mission will survey several hundreds of young stars with ages ranging from a few to several hundred Myr, including weak-line T Tauri stars associated with the closest star-forming clouds (ages 1–20 Myr), X-ray bright young stars in the solar neighbourhood for which accurate distances are known from Hipparcos (ages ~10–100 Myr), and young main sequence stars in open clusters with age >30 Myr. Together, they will produce a phenomenal database for subsequent SPICA spectral imaging of disk evolution around solar-type stars in the planet-forming phase. SPICA will be able to detect disks with only a fraction of a lunar mass throughout the solar neighbourhood.

A graphic illustration of the need for long wavelength imaging and spectroscopy of debris disks is shown by the Spitzer MIPS and JCMT SCUBA images shown in figure 2-13. Here we see the disk surrounding Formalhaut (Stapelfeldt et al 2004) imaged at 24, 70 and 160 µm and the disk around Epsilon Eridani imaged at 850 µm. There is a clear change in the morphology of the disk going from 24 to 70 and longer wavelengths indicating separate populations of dust types and temperatures. However even on this nearby source (7.7 pc) it is impossible to tell at this spatial resolution exactly the size and distribution of the different populations and how they relate to each other and the central star. The mid-infrared instrument on JWST will add considerably to the understanding of the warm component in such circumstances but the cooler component will only be properly observed at longer wavelengths. In fact the warmer 24 µm excess appears to be a relatively rare component in the disks that have so far been observed by Spitzer (Henning priv comm. 2005) and it is essential that observations at 30-60 µm are made with high spatial resolution and good sensitivity to fully understand the lifetime of the dust disk phase of planetary formation.

Although Herschel PACS represents a large increase in the spatial resolution at 70 and 170 µm over both ISO and Spitzer, this leaves a critical wavelength region unexplored between 30 and 60 µm where it seems the transition from one morphology to the other must be happening in this type of source. Also the warm Herschel telescope severely
limits the PACS sensitivity and the ESI on SPICA, with its cold aperture, will enable us to study very much fainter
disks and sample a much more representative population of stars to probe the frequency with which disks are formed
and the evolution of disks as function stellar type.

2.6.3 The Nature of Dust and the “Snowline”
Although broad band imaging of dusty objects, disks, proto-stars, post AGB stars galactic cirrus etc can tell us much
about the size distribution of cosmic dust, one critical aspect that only a spectroscopic instrument with full access to the
mid and far infrared regime can address is the physical composition of the dust itself.

Contained within the 20-60 \( \mu \text{m} \) wavelength range are solid state features of minerals and ices that can be used not only
to determine the composition of the dust but also how and where ice forms on the dust grains within particular
environments. This is of particular importance in the determination of the origins of water within the Solar system. By
studying the location of the “snowline” within proto-planetary disks at different stages of evolution we can determine
when and how the water is formed and locked into ice and therefore whether water in planets is present during their
formation or brought in as part of a later bombardment phase from comets and minor bodies formed further from the
young star.

Evidence for the existence of these spectral features, including the detection of water ice features at 44 and 62 \( \mu \text{m} \), has
been found in many different types of astronomical source by the \textit{ISO} spectrometers (figure 2-14). These two features
can also distinguish the type of ice present as well: only crystalline water-ice has the 44\( \mu \text{m} \) feature, whereas both
crystalline and amorphous water-ice have the 62 \( \mu \text{m} \) feature. The presence or absence of the 44 \( \mu \text{m} \) feature therefore
diagnoses the ice type. The region beyond 25 \( \mu \text{m} \) also contains many diagnostic spectral features of minerals that can
be used not only to determine the make up of the dust but are sensitive to the physical conditions of dust as well, in
particular they act as direct probes of the dust temperature (Hofmeister and Bowey 2005, Bowey et al 2001). Figure 2-
15 gives examples of these detected in highly evolved objects, but the \textit{ISO} spectrometers detected these features in
many different types of object, including protostars and comets. The longer wavelength features are critical in probing
all phases of cosmic dust as at shorter wavelengths we only see the warmer dust (in emission) or very dense regions
where the features are seen in absorption against the spectrum of an underlying warmer source. To probe colder and
more diffuse regions we need to be able to detect the longer wavelength spectral features in emission, indeed in the very
coldest regions these features will also be seen in absorption against background sources, we can thus probe the
physical conditions and dust composition in faint cold galactic cirrus. To detect these features in either emission or
absorption requires very sensitive spectroscopy with the spectral resolution matched to the width of the features in order
to remove systematic effects of instrumental calibration. Although the \textit{ISO} mid and far-infrared spectrometers detected
these features, the poor spatial resolution of \textit{ISO} and difficulties with matching the spectra between the two instruments
means that a full understanding of the origin of these features remains elusive. A SPICA imaging spectrometer
operating from around 30 \( \mu \text{m} \) upwards would represent enormous progress in our understanding of the composition of
cosmic dust in all types of astronomical objects.
Figure 2-14: Combined SWS and LWS spectra of two protostars showing the long wavelength pure H$_2$O ice bands in absorption against the spectrum of the underlying source (Dartois et al. 1998). The same features are seen in emission from cooler objects allowing us to study regions where a warm source and overlying dust are not present.

Figure 2-15: Upper panel examples of post-AGB stars where solid state features have been detected in emission in the FIR the dusty outer envelopes. The lower panel shows the identification of the minerals and ices that give rise to the spectral features. The unique diagnostic features for these minerals lie in the 30-100 µm region.
3. Instrument requirements as dictated by core science requirements

The science cases presented all call for a spectrometer covering the wavelength region from about 25-30 to about 200 µm. However we are left with some important questions about what the exact optimisation of the instrument to obtain the best science. These can be condensed into the following questions about the instrument requirements needed for each scientific project:

- Wavelength range – what do we gain and lose by covering any one particular band?
- Spectral resolution – what resolving power is best suited to each science case, what can we add to the knowledge already gained from other studies?
- Imaging versus single object observation – here we need to consider any benefits of having a true imaging capability against the possible complexity of building an imaging spectrometer. Also, if we are have imaging, what is the minimum useful field of view?
- Finally and perhaps most critically, what is the minimum sensitivity we require in order to push the science beyond what is possible with other existing or planned facilities?

In order to address these questions we have looked at the mission requirements in two ways:

We first look at the basic requirements for a few key science projects that can be taken as limiting cases for the design parameter and which define the core science case for ESI. Secondly we take the mission as a whole and look at how the instrument might actually be used, that is what would astronomers actually do with ESI; we have done this by constructing a “science reference mission” that lays out in detail the types of observing programmes that are likely to be carried out and look at how these dictate the the instrument design.

3.1 Wavelength Coverage

As discussed in section 2.1, there is a compelling case for starting the wavelength band of an instrument at just below 28.5 µm to ensure coverage of the H$_2$ ground state transition at rest wavelengths, and to provide some overlap with JWST. There is also a good case for extending the coverage up to as close to 206 µm as possible in order to cover the ground state [NII] line and as many of the light hydride and atomic cooling lines as practicable, and to allow redshifted FIR lines to be observed in distant galaxies. Certainly coverage up to and beyond the [CII] line at 158 µm is essential for SPICA.

Almost any wavelength range is interesting for high redshift astronomy – however we can begin to set limits by considering as an example two particular lines that will be extremely important in diagnosing the physical conditions in the distant universe. Starting at ~ 28 µm means that the PAH feature at 12.7 µm prominent in nearby galaxies will enter the instrument band at redshifts of z ~ 1.2. Redshift of ~1 – 2 is associated with an apparent peak in star formation rate in the history of the universe. The rather stronger 7.7 µm PAH features begins to enter the band at z ~ 2.4. Similarly the [OIII] 88 µm line appears at about 200 µm at redshift 1.2. An instrument covering 28 to ~200 µm can therefore carry out the same diagnostics at the both the apparent peak of star formation in the history of the universe and in the local universe.

We propose a goal wavelength coverage of 28 to 206 µm for ESI, and, if it proves necessary to restrict the wavelength range for technical reasons, emphasis to be laid on coverage of the shorter wavelength end of the range.

3.2 Spectral resolution

The spectral resolution requirement is essentially driven by the high redshift and local universe science cases. For almost all galactic science the case for very high resolution spectroscopy (R > 10$^6$) is compelling, but is beyond what we are proposing here as much of this can be done by ground (ALMA) or airborne (SOFIA) facilities in the near future. Also, such high resolution is not practical to achieve except using heterodyne techniques which would not exploit the natural advantages of SPICA’s cold aperture. We illustrate the resolution requirements for ESI with three scientific cases – the detection of solid state features, either in absorption or emission; the matching of the natural width of lines in external galaxies for detection and the velocity discrimination of galactic components in our own and nearby galaxies for kinematical studies.

If we study the M82 spectrum we can see that the silicate feature at around 10 µm is ~ 2-3 µm wide. When this is redshifted beyond 30 µm it will appear broader in wavelength and it will be difficult to detect unless we have a reasonably large instantaneous bandwidth and an ability to detect the baseline continuum against which we see the feature in absorption. Similarly the PAH features are broadened and best detected with a resolution that more nearly
matches the width of the redshifted lines. These cases argue for no more than a modest resolution – $R \sim 100$ - with a relatively large instantaneous wavelength coverage. This would also be the easier way to detect the faint molecular, mineral and ice features expected to be discovered in the ISM and proto-planetary disks.

However we do need to ensure that we can avoid blending and overlap for spectral line observations; for instance the [NeII] and PAH features at 12.8/12.7 $\mu$m when redshifted into the ESI band respectively would require a resolution of a few 100 to separate; and we also need to retain the ability to detect weak emission lines against the continuum, which is best done by matching the resolution element to the intrinsic width of the lines – for most external galaxies this is around 100-200 km/s implying an optimum resolution of no more than 1500-3000 for simple detection of these lines.

There is however an argument for pushing to higher resolution as ESI will have, for the first time, the sensitivity necessary to use high spectral resolution.

High spectral resolution is important for the following reasons:

a) Going beyond simple detection of galaxies and actually measure their linewidths to estimate their masses from the kinematics of the gas - this is extremely important for the study of galaxy evolution.

b) Observations of local galaxies and in particular dwarf galaxies is one of the critical science objectives for ESI. Here 300 km/s resolution will result in line dilution and require much longer integration times. To express this more clearly, let us imagine mapping M51 (or M31 or just about any other nearby galaxy) with ESI. Typical line widths are 10 - 50 km/s outside of the centre, decreasing with radius. Several times longer integration times would be required to map the galaxy at $R=1000$ than at $R=10000$ even taking into account the reduction in throughput due to the insertion of a Fabry-Perot.

c) Distinguishing objects along the line-of-sight in Galactic observations; as shown eloquently by the ISOLWS studies of SgrB2 (see figure 3-1) 30 km/s resolution allows one to estimate distances to Galactic objects and distinguish the different spiral arms from each other and thus probe abundances and physical conditions of the ISM as a function of galactic distance. This is not possible with 300 km/s resolution because all of the emission and/or absorption along a given line of sight will be summed into the same velocity channel. Without velocity discrimination, emission from a local hot core and a distant Giant Molecular Cloud will be added together and provide an incorrect picture of the physics at work in either object.

d) Separation of adjacent lines in bright sources where there are very many lines especially from light hydrides such as water and OH as well as their ISOTopes and other more complex molecules. In some cases this may be the only way to
measure the continuum emission. A resolution of around 10000 should enable us to avoid these problems although obviously an even higher resolution is required for detailed dynamical studies of outflows etc.

Given these considerations we propose that the instrument has a baseline resolution of $\lambda/\Delta\lambda \sim 2000$ to allow detection of lines from faint sources. We consider it as extremely desirable that the instrument should also have both a lower resolution “SED” mode and a higher, R~10000, “velocity discrimination” mode.

### 3.3 Imaging capability

The case for an extended field of view for a spectrometer is straightforward for observing both our own and nearby galaxies. The types of objects of interest are almost always extended compared to the beam size of SPICA (~3.5 to 18 arcsec) and even a modest number of spatial pixels (up to a few hundred) would allow major efficiency gains for all scientific projects. In particular nearby proto-planetary disks (such as Epsilon Eridani, Formalhuat, etc.) are of order of a few arcmin in size and an imaging capability will pay dividends in the speed of spectrally mapping such sources.

SCUBA data and simulations of high-redshift galaxy counts suggest that clustering is present on a scale of a few arcminutes; a field of view of a few arcminutes would therefore provide an observing efficiency gain as one gains both by simultaneous measurement of the background close to the target and by the number of sources within a single field of view.

As a baseline we propose an imaging spectrometer with a field of view of at least 60 arcsec – this would give a respectable 15 x 15 pixels at 50 $\mu$m. We set a goal for the FOV to be as large as practicable up to the limit available in the SPICA focal plane (3.8 x 3.8 arcmin). This must, of course, be seen in the context of any increases in complexity and resource requirements of the instrument.

### 3.4 Required Sensitivity

We take as the limiting case for the sensitivity requirements the need to detect the emission lines from a starburst galaxy such as M82 when redshifted to beyond $Z\sim 1$. Looking at the ISO SWS and LWS spectrum for M82 we can take as limiting a case the need to examine the NeIII(15.6)/NeII(12.8) ratio (see Thronley et al 2000) and the OI(63) line. Based on examination of the ISO SWS and LWS spectra and calculating the luminosity distance using a Universe with $H_0 = 70$ km/s Mpc$^{-1}$, $\Omega_m = 0.30$, $\Lambda_0 = 0.70$, $q_0 = -0.55$ and $k=0$; we get the values of the line flux given in table 3-1. We include for completeness the CII(157) line although this will be redshifted beyond the ESI band for $z>0.3$ it should be a goal for the BLISS instrument on SPICA. Based on these estimates we see that an FIR spectrometer requires sensitivity of ~a few x10$^{-21}$ W m$^{-2}$ to detect an M82 class galaxy in the faintest of these diagnostic lines up to $z\sim 2$ and on the more typical luminosity objects (5-10 times M82) to redshifts of 3. We take this as the goal for the ESI instrument sensitivity.

<table>
<thead>
<tr>
<th>Z</th>
<th>M82 Distance (MPc)</th>
<th>Luminosity Distance (MPc)</th>
<th>Dilution</th>
<th>M82 NeII Line flux</th>
<th>M82 NeIII Line flux</th>
<th>M82 OI Line flux</th>
<th>M82 CII Line flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.3</td>
<td>3.01E-03</td>
<td>1.21E-15</td>
<td>2.11E-16</td>
<td>1.90E-15</td>
<td>1.39E-15</td>
<td>3.21E-19</td>
</tr>
<tr>
<td>0.01</td>
<td>43</td>
<td>1.05E-05</td>
<td>1.85E-18</td>
<td>1.66E-17</td>
<td>1.22E-17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>460</td>
<td>1.00E-06</td>
<td>2.78E-19</td>
<td>4.87E-20</td>
<td>4.37E-19</td>
<td>3.21E-19</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>2833</td>
<td>5.11E-20</td>
<td>8.96E-21</td>
<td>8.03E-20</td>
<td>5.91E-20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6607</td>
<td>2.21E-07</td>
<td>1.62E-21</td>
<td>1.45E-20</td>
<td>1.07E-20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>15539</td>
<td>9.24E-21</td>
<td>1.62E-21</td>
<td>1.45E-20</td>
<td>1.07E-20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>25422</td>
<td>3.45E-21</td>
<td>6.05E-22</td>
<td>5.43E-21</td>
<td>3.99E-21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>35851</td>
<td>1.74E-21</td>
<td>3.04E-22</td>
<td>2.73E-21</td>
<td>2.01E-21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>46652</td>
<td>1.03E-21</td>
<td>1.80E-22</td>
<td>1.61E-21</td>
<td>1.18E-21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-1: The estimated line brightness in W m$^{-2}$ for representative lines seen in the ISO spectrum of M82. The line fluxes are taken from examination of the processed products in the ISO Data Archive and agree closely with values published by Förster-Schrieber et al (2001) for the mid-infrared lines. We have assumed a line width of ~150 km/s in calculating the strength of the OI and CII lines from LWS grating spectra which do not resolve the lines.

### 3.5 Science Reference Mission

The way that astronomers might actually use the ESI is discussed at some length in the preliminary Science Reference Mission. Here we summarise the results of that analysis.

Observation types are mostly extended sources, or point sources embedded in a larger structure. This implies a need for full spatial sampling and for a reasonable field size. Several applications are concerned with mapping large objects; for these the largest field possible would be best. Those projects that would benefit from something smaller, but larger than
1 point, have characteristic scales of about 2 arcminutes. This is sufficiently large that a proto-planetary disk will fit inside the field with sufficient ‘off source’ size to define the background, while it is roughly the size of a high redshift galaxy cluster core. If a field size less than maximum needs to be chosen, then something around 2 arcminutes across would be the next best option.

Most of the projects listed in the Science Reference Mission would benefit considerably from having access to the full spectral range in a single observation. This may be partly because the reference mission described here contains a large number of spectral survey-type projects, but this also reflects our relatively poor knowledge of this waveband.

Many of the projects require good photometric accuracy since they are looking at both lines and continuum. This is largely the result of needing to do searches for lines and broad features amid the continuum. Those that do not require characterisation of the continuum are generally concerned with studies of specific lines at known wavelength. More information is needed about likely sensitivities before actual figures can be placed on integration times.

In summary taking this “user-centred” approach we come to essentially the same instrument definition as the core science case: a moderate resolution imaging spectrometer with the ability to cover the entire wavelength range as rapidly as possible.

4. Instrument concept

4.1 Types of Spectrometer Considered

We have two basic choices for the type of spectrometer we can employ – a monochromator device such as a grating or Fabry-Perot or a broadband device such as on FTS. Given that we wish to have available the possibility to have two different resolutions we also need the ability to offer a flexible resolution – such as an FTS could give – or to have the ability to insert a different type of spectrometer to increase the resolution – such as a high resolution Fabry-Perot. In Table 4-1 we give the various options and an indication of the possible advantages and disadvantages of each.

<table>
<thead>
<tr>
<th>Spectrometer type</th>
<th>Low/medium resolution</th>
<th>Wide Instantaneous Bandwidth</th>
<th>High Resolution</th>
<th>Imaging</th>
<th>Flight Heritage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grating</td>
<td>Yes</td>
<td>Yes</td>
<td>By inserting F-P</td>
<td>Image slicer with small FOV</td>
<td>ISO LWS and SWS Herschel PACS</td>
</tr>
<tr>
<td>FTS</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes Possibly with insertion F-P</td>
<td>Yes large FOV</td>
<td>Astro-F SPIRE</td>
</tr>
<tr>
<td>Tandem F-P</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>None (except KAO)</td>
</tr>
</tbody>
</table>

Table 4-1: Summary of basic capabilities of various generic types of spectrometer

**Grating spectrometers** – most aspects are well understood and no development is required except in the area of dichroics/filters to allow us to use multiple orders from a single grating over such a large waveband. However the difficulty envisaged with giving a grating instrument a large field of view means that we have chosen not to take this as the baseline but rather to leave serious study of a grating option until a more fully funded Phase A study.

**FTS** – here the major issue will be whether we can use a single beam splitter over a large wavelength range. It is desirable not to have variety of beam splitters with the attendant need for interchange wheels. A polarising FTS would work (as demonstrated on Astro-F) but the polarising grids may require some development to work over the large wavelength range efficiently. The present state of the art in broadband amplitude beam splitters (as developed for Herschel-SPIRE) offers a potential factor of 6 in wavelength coverage. The choice for any instrument based on currently available technology is therefore to cover either 34.5 - 206 µm or 28-168 µm, depending on which of the important lines discussed in section 2.1 is given priority.

**Fabry-Perot** – efficient etalons are required both for any medium resolution device and, more critically, for a high resolution device. We would anyway need three F-Ps to cover the wavelength range as the physics of these devices makes using them over a large wavelength range rather difficult.

4.2 Baseline Instrument Concept

The instrument concept that most closely matches the scientific requirements for resolution, imaging and flexible spectral resolution is the FTS. We have taken this concept as the starting point for ESI and worked through a reasonable set of assumption to show that it is at least conceptually possible to implement this in the context of the
SPICA mission. We describe here the basic conceptual design for the focal plane unit and discuss the options for detectors layouts and technologies, the sensitivity achievable and the technology developments required to implement the instrument. We use this instrument concept to formulate the requirements we will place on the SPICA mission in section 7.

4.2.1 Outline Focal Plane Layout

Figure 4-1 shows a dimensionally correct sketch of an instrument concept based on the Herschel-SPIRE spectrometer design. Here we show a set of fore-optics that conditions and collimates the SPICA beam before injecting into a long collimated section through the Mach-Zehnder FTS. Figure 4-2 shows how the injection might be arranged by taking the beam out of plane. In order to use the two input ports efficiently, a dichroic is used to split the light into a short and long wavelength beam. Each beam takes a separate route through the interferometer and each output port covers the same wavelength range. In order to keep the spatial sampling correct at all wavelengths the beams are further chromatically split in the camera section. In figure 3 we show how this might be achieved in concept – each output port can have one or two detectors. The detector arrays themselves will be placed physically close together in order to simplify the mechanical and thermal architecture of the coldest part of the instrument.

The main body of the optics and spectrometer will be kept at 4.2 K with only the detector housing at 1.7 K or below in the case of the use of thermal detector arrays.

Figure 4-1: Layout of spectrometer showing how it might be fitted into the SPICA focal plane volume
4.2.2 Spectrometer Design Parameters

The outline design of the spectrometer is predicated on the following baseline system design parameters:

Wavelength coverage \( \lambda = 27 - 206 \, \mu m \) or \( 48.5 - 370 \, \text{cm}^{-1} \)

Required resolution \( \lambda / \Delta \lambda = 2000 \) at \( 100 \, \mu m \) (100 cm\(^{-1}\))

\( \Rightarrow \Delta \sigma = 0.05 \, \text{cm}^{-1} \)

Optical path difference \( \Delta \sigma = 1.22/(2L) \Rightarrow L = 12.2 \, \text{cm} \)

assume 14 cm for scan length to allow for measure of zero path difference

Linear travel This will be \( \frac{1}{4} \) due to the folding of the optical path inherent in the Mach-Zehnder design (14 cm)/4 = 3.5 cm (from -0.45 to +3.05 cm w.r.t. ZPD)

Position measurement: OPD accuracy required minimum = 2.5/50 = 0.05 \( \mu m \) (50 nm)
Actual position measurement = 50/4 = 12.5 nm

Additionally we need to size the optical beam diameter required for the collimated section of the optical path through the spectrometer as this sizes the instrument. In order to ensure that the OPD doesn’t vary significantly over the extent of a single spatial element, the minimum beam size at the limiting pupil stop in the FTS is given by (Dohlen 2000)

\[ D_{\text{FTS}} > \sqrt{R \lambda D_T \phi} \]

The limiting case is at the longest wavelengths \( \Delta \sigma = 0.05 \text{ cm}^{-1} \) at 200 \( \mu \text{m} \) \( R = 1000 \) therefore for \( D_T = 3500 \text{ mm} \) and \( \phi = 3.8 \text{ arcmin} \) (circular), \( D_{\text{FTS}} \sim 30 \text{ mm} \) – we should take 40 mm for adequate margin and to cover to the edges of a square array; for a 1 arcmin FOV \( D_{\text{FTS}} \sim 15 \text{ mm} \). We will design for a pupil size of 40 mm until this becomes a problem.

**Figure 4-4:** First cut optical analysis of the instrument concept. The fore optics and one side of the spectrometer are shown. The rays are traced for a ±0.5 arcmin FOV, 6 arcmin off axis; the focal planes shown are sized to 3.8x3.8 arcmin

**Figure 4-5:** More detailed view of the ray paths through the instrument. Left a side view and right a 3-D view. Only one arm of the FTS is shown and the locations of the pupil images and dichroics needs further work as part of the ongoing study.

### 4.2.3 Basic Optical Design

A proof of concept exercise for the optical layout has been carried out on the outline design. Figures 4-4 and 4-5 show the results in relation to the SPICA telescope. This first cut analysis shows that the outline design will work in principle but detailed work is required, for instance, to place the pupil images in the correct place and control off axis aberrations etc. Although more work is required, and the detailed layout may change as the design matures, this study shows that the basic instrument is feasible optically and that a reasonably wide field of view will be attainable.
4.2.4 Number of detector bands

The optical concept will allow us to have up to four detector arrays – two per chromatic “side” of the spectrometer. We have looked at three options for the division of the bands, the spatial sampling the size of the FOV to illustrate the issues associated with detector and FOV choice. The basic choice is between three and four bands as follows:

3 Bands
Band 1 – 27-58 µm centred at 42.5 (172 -370 cm⁻¹)
Band 2 – 58-100 centred at 79 (100 – 172 cm⁻¹)
Band 3 – 100-206 µm centred at 153 (48 – 100 cm⁻¹) or

4 Bands
Band 1 - 25-40 µm centred at 32.5 (250 - 400 cm⁻¹)
Band 2 – 40 - 60 µm centred at 50 (167 - 250 cm⁻¹)
Band 3 – 60 – 100 µm centred at 80 (100 – 167 cm⁻¹)
Band 4 – 100 – 210 µm centred at 150 (50 – 100 cm⁻¹)

The edges of the bands will be fine tuned to the detector technology needs as part of the ongoing study. We layout the numbers of pixels required in tables 4-1, 4-2 and 4-3.

Table 4-1: Option 1: 3 Band - 1 arcmin FOV minimum spatial sampling

<table>
<thead>
<tr>
<th>Band</th>
<th>Lambda_central</th>
<th>PSF (arcsec.)</th>
<th># PSF/FOV</th>
<th>No: pixels required to minimally sample FOV</th>
<th>Pixel size (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>42.5</td>
<td>3.05</td>
<td>20</td>
<td>40x40</td>
<td>1.5</td>
</tr>
<tr>
<td>Band 2</td>
<td>79.0</td>
<td>5.7</td>
<td>10</td>
<td>20x20</td>
<td>2.8</td>
</tr>
<tr>
<td>Band 3</td>
<td>153.0</td>
<td>11.1</td>
<td>6</td>
<td>12x12</td>
<td>5.55</td>
</tr>
</tbody>
</table>

Total of 1600, 400 and 144 pixels – 2144 pixels. Here the sampling at the shortest wavelength part of the bands will be marginal and it will be difficult to recover the spatial resolution delivered by the telescope. This option represents the probable maximum available array size for photoconductor technology - see discussion on photoconductor arrays

Table 4-2: Option 2: 3 Band - 1 arcmin FOV fully spatially sampled over band

<table>
<thead>
<tr>
<th>Band</th>
<th>Lambda_central</th>
<th>PSF (arcsec.)</th>
<th># PSF/FOV</th>
<th>No: pixels required to minimally sample FOV</th>
<th>Pixel size (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>42.5</td>
<td>3.05</td>
<td>20</td>
<td>80x80</td>
<td>0.75</td>
</tr>
<tr>
<td>Band 2</td>
<td>79.0</td>
<td>5.7</td>
<td>10</td>
<td>40x40</td>
<td>1.45</td>
</tr>
<tr>
<td>Band 3</td>
<td>153.0</td>
<td>11.1</td>
<td>6</td>
<td>24x24</td>
<td>2.77</td>
</tr>
</tbody>
</table>

Total of 6400, 1600 and 576 pixels - 8576. This nearly samples properly over each part of the band, except at the very shortest end of Band 1, and is the real minimum option for full recovery of the SPICA spatial resolution.

Table 4-3 Option 3: 4 Band - 3.8 arcmin FOV with full spatial sampling over band

<table>
<thead>
<tr>
<th>Band</th>
<th>Lambda_central</th>
<th>PSF (arcsec.)</th>
<th># PSF/FOV</th>
<th>No: pixels required to fully sample FOV</th>
<th>Pixel size on sky</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>32.5</td>
<td>2.3</td>
<td>99</td>
<td>256 x 256</td>
<td>0.89</td>
</tr>
<tr>
<td>Band 2</td>
<td>50.0</td>
<td>3.5</td>
<td>65</td>
<td>256 x 256</td>
<td>0.89</td>
</tr>
<tr>
<td>Band 3</td>
<td>80.0</td>
<td>5.7</td>
<td>40</td>
<td>160 x 160</td>
<td>1.42</td>
</tr>
<tr>
<td>Band 4</td>
<td>150.0</td>
<td>10.6</td>
<td>21.5</td>
<td>80 x 80</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Total pixels 65536, 65536, 25600, 6400 pixels – 156832 pixels. This represents the largest possible array sizes and is almost certainly beyond the scope of any current technology – it does serve to illustrate the maximum resources that the ESI would need. Even here the beam will be under sampled at the short end of Band 1 with the proposed array this is because the arrays for Bands 1 and 2 have been chosen to be identical in order to reduce costs. We will also consider a four band instrument with a FOV of 2x2 arcmin – i.e. with ¼ the number of pixels.
Physical pixel and array size:
We take option 3 as the limiting case for pixel and array size. Assuming a telescope with a focal ratio: ~7±0.2 (assuming EPD=3.45m on M1 with DM1=3.5m) and a focal length of ~24.15±0.5m; the image scale at the telescope focal plane will be ~8.54″/mm (=0.14arcmin/mm). If we assume no magnification at the output focal plane the pixel sizes and array sizes will be:

Pixel size: Band 1 = 104 µm; Band 2 = 104 µm; Band 3 = 166 µm; Band 4 = 310 µm – such a small pixel size may not be feasible with either photoconductor or bolometer technologies and some magnification may be required.

Array size: All arrays will be ~27 mm square with 1:1 imaging.

4.3 Instrument Sensitivity
We have estimated the instrument sensitivity based on the currently available photoconductor technology and a potential future development of bolometer arrays that will give NEP’s in range the of 1x10⁻¹⁹ W Hz⁻¹/² – we have looked at two cases: the basic instrument design with a full spectral band FTS as described above, and the case where by some means we have a band limited spectrometer - grating, Fabry-Perot etc.

Figure 4-6 shows the NEP for the currently available photoconductor technology compare to the expected photon noise from the Zodial light for the instrument as described with no band limiting (the assumed spectrum is also shown) and the goal NEP for a future development of bolometer arrays. In figures 4-7 and 4-8 we show what this would mean in terms of the instrument’s ability to detector continuum and lines. We can see that with present state of the art detectors we will detect lines of ~1 x 10⁻¹⁹ W m⁻² to 5-σ in 1-hour; if we achieve the goal detector sensitivity the detection limit will be ~7x10⁻²⁰ W m⁻². In the one case we detect the critical [OI](63) line in M82 type galaxies at z~0.5-1, in the other out to z~1.5.

![Figure 4-6](image-url)

Figure 4-6: Left hand panel – the assumed spectrum of the Zodiacal light used in estimating the sensitivity of ESI (based on Wright 1996). Right hand panel - estimated NEP referred to the detector for various noise sources in the ESI concept instrument assuming the three band option. The solid purple line is the detector noise (only) for current photoconductor technology. The solid green line shows the goal 1x10⁻¹⁹ W rt(Hz) NEP for future bolometer arrays and the dashed green line is the Zodical limited NEP for broad band detection assuming a quantum efficiency of 0.5.
Figure 4-7: Continuum detection ability of ESI for photoconductors (purple) and assumed goal detector performance (green). The solid line is for $\Delta \sigma = 5$ cm$^{-1}$ the dashed line is for the full band imaging with the FTS parked at zero path difference.

Figure 4-8: Calculated FTS sensitivity to unresolved lines – solid green and purple lines with no points – colours as for figure 4-7. Here we compare the predicted sensitivity levels to the line strengths for M82 at various red shifts taken from table 3-1 – solid lines with diamonds – species and redshifts as indicated. We also plot (dashed lines with crosses) the NeII and NeIII fluxes for a, possibly more typical, galaxy 10 times brighter than M82.
**Band Limiting**

Figures 4-7 and 4-8 show us that a broad band FTS limited by the Zodiacal background is well matched to present detector sensitivities. However, if we wish to take full advantage of any significant increase in the sensitivity newly developed detectors we will need to have some form of spectral band pass limited. This is illustrated in the figure 4-9 where we recalculate the NEPs and line sensitivity for an instrument band limited to R~200 and a throughput reduced by 30%. Here we see that there is a much larger difference between the start of the art detector sensitivity and the development detector sensitivity: in this scenario the instrument will achieve ~$1-2 \times 10^{-20}$ W m$^{-2}$ line sensitivity and M82 would be detectable in [NeII](15.6) at redshifts of 1-1.5 and in [OII](63) at redshifts up to 2.

We have not considered in this initial study how band limiting might be implemented or which other features of the instrument would have to be changed (FOV etc) in order to achieve a band limited design.

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Figure 4-9: NEP (left) and line sensitivity (right) for an instrument with R~200 and a throughput reduced to 30% that of the full band FTS. Colours and line styles as for figure 4-7 and 4-8
5. Development Requirements

5.1 Current detector technologies and development needs

The astrophysical background radiation has a broad minimum in the Far Infrared (FIR) region of the spectrum dominated by the emission from the Zodiacal light. Reducing the level of radiation from the nearby environment of an astronomical instrument to a level comparable with the astrophysical background requires the use of cooled optics on a satellite such as SPICA. Taking full advantage of this low level of background radiation requires detectors with extremely high sensitivity.

Currently, the state of the art detectors for this region of the spectrum are photoconductors such as Ga:Ge and Si:Sb. These types of detectors have been flown on previous space missions such as IRAS, ISO and Spitzer, however, the sensitivity, quantum efficiency and wavelength coverage from these detectors limits the overall performance of a FIR instrument for SPICA. A number of groups are developing new detector technology to address these limitations. Table 5-1 summarises some of the current developments

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>NEP (W/√Hz)</th>
<th>τ</th>
<th>Operating T (K)</th>
<th>Heritage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photoconductor (e.g. Ga:Ge)</td>
<td>$10^{-19}$</td>
<td>~1 ms</td>
<td>&lt; 2 K</td>
<td>ISO, Spitzer</td>
</tr>
<tr>
<td>Semiconductor bolometer</td>
<td>$10^{-17}$</td>
<td>~1 ms</td>
<td>300 mK</td>
<td>HERSCHEL</td>
</tr>
<tr>
<td>TES bolometer</td>
<td>$&lt; 10^{-18}$</td>
<td>~1 µs</td>
<td>100 mK</td>
<td>SCUBA2</td>
</tr>
<tr>
<td>Kinetic Inductance Detector</td>
<td>$&lt; 10^{-16}$</td>
<td>~1 µs</td>
<td>100 mK</td>
<td>None</td>
</tr>
<tr>
<td>Cold Electron Bolometer</td>
<td>$&lt; 10^{-16}$</td>
<td>~10 ns</td>
<td>300 mK</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 5-1: Currently measured sensitivities for different types of FIR detectors.

One of the challenges to achieving improved detector sensitivity with bolometric detectors is the extremely low levels of optical power expected on SPICA. Even with an FTS instrument covering a large bandwidth at a wavelength of 100 µm, the astrophysical and telescope background power level is on the order of $10^{-16}$ W. The photon shot noise in such a system would be on the order of $10^{-19}$ W/√Hz, an order of magnitude lower than the sensitivity of standard photoconductors. Superconducting thermal detectors, such as TES bolometers, Kinetic Inductance Detectors and Cold Electron Bolometers have the potential to offer improved sensitivity in large format lithographed arrays combined with cold multiplexing readouts. However, these detectors all require sub-Kelvin cooling in order to achieve the improved NEP to existing photoconductors and are still very much under development. Systems for cooling semiconductor bolometers to 300 mK and TES bolometers to 100 mK have flown already on several missions and are planned to fly on Herschel and ASTRO-E2.

During the concept study phase for ESI we have looked in more depth at two possibilities for future developments of large format arrays: photoconductors and TES bolometers. We have also looked into the thermal requirements of both these technologies and the resource implications for the SPICA system.

5.1.1 Photoconductor Options

The low dark current at comparatively moderate, and therefore ‘less demanding’, operating temperatures give photoconducting detectors a clear advantage over thermal detectors. This is especially the case for the SPICA satellite where thermal detectors require additional sorption /ADR coolers to be operated with a NEP comparable to photoconductors available to date (see section 6.1 below). The following state of the art photoconductor materials have been studied: Ge:Ga both stressed and unstressed, Si:Sb, Ge:Be, and GaAs as a material that is still under development at the present time, but could be available within the next few years. In Table 5-2 we summarise the basic properties of the photoconductor options possible for the ESI instrument.

<table>
<thead>
<tr>
<th>Material</th>
<th>Technology</th>
<th>Wavelength</th>
<th>Temperature</th>
<th>NEP/read noise</th>
<th>Largest to date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge-Ga, unstressed</td>
<td>bulk</td>
<td>40 – 110µm</td>
<td>1.8K</td>
<td>---</td>
<td>32 x 32 (MIPS)</td>
</tr>
<tr>
<td>Ge-Ga, stressed</td>
<td>bulk</td>
<td>100 – 210µm</td>
<td>2.2K</td>
<td>$10^{-18}$ W/√Hz</td>
<td>25 x 16 (PACS)</td>
</tr>
<tr>
<td>Si:Sb</td>
<td>BIB</td>
<td>12 – 40µm</td>
<td>4K</td>
<td>30 e$^{-}$ read noise</td>
<td>128 x 128</td>
</tr>
<tr>
<td>Ge:Be</td>
<td>bulk</td>
<td>30 – 50µm</td>
<td>4K</td>
<td>$10^{-17}$ W/√Hz</td>
<td>1 x 12 (ISO)</td>
</tr>
<tr>
<td>GaAs</td>
<td>bulk or BIB</td>
<td>50 – 330µm</td>
<td>1.5 – 2.5K</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 5-2: Summary of photoconductor properties.

Comments:

1. Building stressed pixel stacks is extremely challenging and the limits of the method used for the PACS arrays need thorough investigation.
2. The issue of detector time dependence - especially pronounced at low backgrounds such as present on SPICA - and cosmic ray effects need further investigation.
3. Although GaAs BIB devices offer an extremely large wavelength coverage and the possibility of large-scale arrays, the material is still under development and not ‘state of the art’ technology.

**Required photoconductor technology for a SPICA instrument:**

Based on the photoconductor technology currently available, the proposed wavelength band between 25 and 200 µm can be effectively covered with the following three or four detector bands:

- **Band 1:** 25 –40µm using a SiSb BIB array.
- **Band 2:** 40 – 110µm as a single band with unstressed Ge:Ga or two separate bands 40 – 50 and 50 – 110µm with Ge:Be and unstressed Ge:Ga respectively.
- **Band 3:** 110 – 210µm using stressed Ge:Ga detectors.

The edges of these bands are defined by the spectral response of the detector materials, but can be slightly adjusted according to spectrometer requirements.

**Photoconductor read-out:**

Bulk type photoconductors such as Ge:Ga suffer from significant de-biasing and require active amplifier read-out circuits. As a baseline read-out for the Ge:Ga pixel arrays we propose Capacitive Feedback Transimpedance Amplifier (CTIA) in CMOS technology as operated in the PACS instrument. The nominal operating temperature ranges from 1.7 to 4K, with a total power dissipation of 100µW for an 18 pixel read out. Various options for coupling the read-out circuits, or individual electronic building blocks to the available temperature levels have been investigated. In either case, the power consumption of the read-out electronics will limit the number of pixels. The maximum detector size available within the given thermal budget needs still to be determined and is part of the ongoing study.

### 5.2 TES Bolometer Arrays

**Background:** Transition Edge Sensors (TES) are the most well developed technology of a new generation of high sensitivity superconducting detectors (see Table 5-1). Operating as bolometers, TES thermometers are used to measure the minute rise in temperature produced by photons incident on the absorber onto which the TES is mounted. Their response is to first order frequency-independent, depending on the properties of the absorber and optical coupling. TES are operated in voltage-biased mode: the increase in physical temperature caused by the absorbed photon increases the detector resistance translating to a reduction in the current flowing through the TES-bias circuit which is monitored using a low-impedance, low-noise SQUID. Both the TES and SQUIDs are planar in structure, and so are straightforward to both fabricate and array. The total number of wires required to operate the TES and SQUID is large, however, and multiplexing is needed if low thermal loading and compact detector packing are to be achieved.

**Sensitivity:** The sensitivity of a TES is limited by phonon noise, with the NEP (sqrt(4kTG)) dependent on operating temperature and the thermal conductance, G. To achieve background-limited performance with the ESI places a requirement on the detector NEP of <10^-18 W/Hz^1/2 which, at a practical operating temperature of ~100mK, translates to Gs (thermal conductances) of less than 10^-12 W/K. Whilst this is more than a factor of 10 lower than the typical values of existing low-background detectors, theoretical work that we have undertaken suggests that it will be possible to achieve the required Gs by optimising the configuration of the structures that couple the bolometer to the cold heat sink. TES detectors with a range of configurations are currently being fabricated at SRON in order to confirm this.

**Dynamic Range:** The low thermal conductances that are key to achieving high detector sensitivity restrict the detector dynamic range. This is set by the difference between the base temperature of the cryogenic cooler and the transition temperature of the TES, typically about T~30-50 mK, and the thermal conductance, and means that astronomical sources with continuum flux densities much in excess of 50mJy in any of the FTS bands will saturate the TES. It is important to note that it is the integrated flux across the band – both the line and underlying continuum – and not just the line that contribute. It will therefore be necessary to reduce the astronomical signal when observing bright, galactic sources using neutral density filters (or crossed polarisation grids) or to change the thermal conductance of the TES using superconducting heat links. One key feature that differs between the operation of TES in space and on ground-based telescopes is the combined loading contribution from the sky and the telescope: the dominant background contribution comes from the zodiacal light: this is both fixed and negligible over ESI wavebands. No heaters are therefore required to compensate for a range of observing conditions.

**Detector speed and sampling rates:** The speed of response of TES detectors depends on the heat capacity of the thermometer and absorber, C, the thermal conductance, G, and the slope of the resistance vs. temperature curve of the superconducting transition. In ground-based applications with relatively large background loading, typical TES time constants are in the microseconds. For the lowest thermal conductance devices we have modelled, the time constant is on order of 10 ms, giving a detector signal bandwidth of approximately 20 Hz.

Independent of the details of the multiplexing scheme used for the readout, the overall sample rate required by the system is approximately 10 times the signal bandwidth per detector or 200 Hz x the number of detectors. Because the
SQUID readouts inherently remove the highest significant bits of the signal and convert them to cycles on the characteristic $V-\phi(I)$ curve, the data can be sampled with standard 12-bit analog to digital converters.

**Array Footprint and spatial sampling:** The number of pixels needed to satisfy even the most basic of the FTS options requires multiplexing of the TES bias and read-out electronics. This is necessary not only to minimise thermal loading but also, very importantly, to achieve a compact array design. Multiplexing can be done in either the time (TDM) or frequency-domain (FDM). The physical number of detectors that can be multiplexed under the two schemes is approximately equal, however the two approaches impose different constraints on the detector bias electronics, array layout, detector packing and signal processing electronics. The footprint of an individual TES pixel is dominated by the lithographic features of the capacitors and inductors needed in the filtering circuits (FDM) or by the physical size of the first-stage SQUID amplifier (one required per TES for the TDM approach): in both cases this is order of a few square millimetres which is a factor of more than 10 greater than that available with the proposed f/20 optics. A compact layout can be achieved by adopting the FDM approach, and moving the individual LC filters to the edge of the multiplexed arrays, reducing the individual detector footprint to ~250umx250um.

### 5.3 Other technology developments required

**Mechanisms**

The ESI concept presented here needs at least one mechanism for the FTS mirror drive. The mechanism developed for the Herschel-SPIRE instrument has the correct capabilities for ESI:

- Step resolution ~2 µm
- Position accuracy ~10 nm
- Drive speed up to 0.5 mm/s
- Range -0.4 to 35 mm

However it requires a reasonable amount of power average ~3mW (1.1mW for the actuator, 1.9mW for the optical encoder and 0.1mW for the LVDT). This could be reduced by the development of piezo-electric or super-conducting coils for the actuator. Piezo-electric mechanisms offer the possibility of very low cryogenic power dissipation but there is little flight heritage and the movement range may be limited. Super-conducting actuator coils have flown on Spitzer. As part of the Phase A study, we will investigate the issues of flight qualification for both these types of devices and the systems impacts of the electronics to drive them etc.

The ESI may also require interchange wheels and a possible scanning drive for a chopping mirror. Many different solutions for these types of mechanism exist and have been, or will be flown. We will survey the different options and evaluate them in the light of the systems requirements from SPICA and the instrument design.

**Optical Components**

Although most optical components required for the ESI concept have been, or will be, flight proven on ISO, Spitzer and Herschel, beam splitters, dichroics , filters and polarisers all require some development. Development is especially required in taking technology already proven at longer wavelengths (40 µm and above), to the shorter part of the envisaged band.
6. Spacecraft budgets and interfaces

6.1 ESI Spacecraft Interface Summary

Table 6-1 summarises the current best estimates of the instrument to spacecraft interface budgets for both the Photoconductor detector array option and the TES detector array option working at ~100mK with a cascaded hybrid 3-He Sorption Cooler and ADR system. It must be stressed that the figures presented are preliminary and subject to revision during subsequent studies and development programmes.

One of the main conclusions from this initial feasibility study is that the resources provided by the spacecraft are adequate to make the ESI instrument feasible.

Table 6-1: Initial estimates and notes regarding the instrument to spacecraft interface budgets.

<table>
<thead>
<tr>
<th>Interface</th>
<th>Description</th>
</tr>
</thead>
</table>
| Thermal budget: Photoconductor detector option (critically sampled 1’x1’ FOV with Cold Readout Electronics at 20K) | 20K Stage:  
• Parasitic heat load from instrument cryoharness: TBD mW  
• Cold readout electronics: 5.4mW  
4.5K Stage:  
• Parasitic heat load from cryoharness: 2.9 mW  
• Primary Focal Plane Unit Mechanism dissipation: < 5mW  
2.5K Stage  
• Detector harness parasitics: 23.4µW  
1.7K Stage  
• Detector harness parasitics: 4.3µW  
• Detector array structural parasitic heat load (4.5K to 1.7K): 2mW |
| Thermal budget: TES detector and hybrid sub-K cooler option | 20K Stage:  
• Parasitic heat load from instrument cryoharness: TBD mW  
4.5K Stage:  
• Heat load from 3-He Cooler:  
  • During operation ~11mW and during recycle ~13.3mW  
• Parasitic heat load from cryoharness:  
  • TBD mW  
• Primary Focal Plane Unit:  
  • Mechanism dissipation ~ 5mW  
2.5K Stage  
• Thermal shunt from 3-He cooler: ~ 10mW during recycle otherwise negligible  
1.7K Stage  
• Latent heat load during condensation phase: ~1-2mW  
• Detector array structural parasitic heat load (4.5K to 1.7K): 2mW |
| Mass | Focal Plane Unit: 64kg  
Cryoharness: 10kg  
Warm Electronics:  
  • DPU: 10kg  
  • Analogue: 60kg |
| Electrical Power | DPU: 20W  
Analogue: 150W |
| Telemetry | Less than and average of 2.8 MBits/s post compression (30GBytes / day) |
| Volume | Cold units:  
  • Cold Units height: < 500mm  
  • Cold unit footprint: within envelope of 1100x550mm  
Warm units:  
  • DPU: 300x300x200mm  
  • Two analogue Units: 500x300x300mm |
| Pointing | < a few arcsec blind pointing  
  Stability better than 0.5 arcsec over 5 minutes |

6.2 Structural design

The primary requirements on the structural design of the Focal Plane Unit are that (i) the structure is sufficiently stable that the optical components meet the optical tolerance budget at the operating temperature, (ii) the strength and stiffness
of the mechanical components is sufficient to withstand the launch environment (iii) the thermal isolation between the various thermal stages meets the ESI internal thermal budgets and (iv) the mechanical design of the instrument is compatible with the interface with the spacecraft optical bench.

A trade-off study needs to be conducted to make the decision between using Aluminium alloy or sintered C-SiC for the main structure. 6-2 summarises a relative comparison between the two materials. One distinct advantage of C-SiC is that it is the same material as the spacecraft optical bench and therefore the differential thermal contraction would be matched to the instrument. If the structure were constructed from Aluminium alloy, then the differential contraction would have to be taken into account via an Isostatic mount mechanism.

In addition to the technical considerations, several non-technical points need to be taken into account in the trade-off – for example instrument model philosophy, development schedule, cost etc. Nonetheless, the fundamental feasibility of the design of the instrument does not depend on the choice of material as the structural requirements outlined above could be met with either option.

Table 6-2: Comparison between C-SiC and Aluminium Alloy for the main structure

<table>
<thead>
<tr>
<th></th>
<th>Aluminium Alloy</th>
<th>C-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness (Young’s Modulus)</td>
<td>Average</td>
<td>Excellent</td>
</tr>
<tr>
<td>Strength</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Fracture toughness</td>
<td>Good</td>
<td>Average</td>
</tr>
<tr>
<td>CTE</td>
<td>Good (in terms of stability)</td>
<td>Excellent (stability and magnitude) + compatible with S/C optical bench</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Density</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

6.3 Thermal architecture

Overview

There are currently, two candidate detector technologies which could be utilized in ESI. The first is a photoconductor detector array operating at a temperature of 1.7K and the second is a TES bolometer array operating at a temperature of ~100mK. The thermal architecture required to successfully implement both of these options have been studied separately but share some common features:

1. The available overall instrument mass budget is modest, so the design of the hardware must be optimised to achieve a minimum mass solution.

2. The cryogenic heat lift is limited by the capacity of the 3-He and 4-He Joule-Thompson coolers. The overall thermal architecture of the instrument must be optimised to limit both the dissipative and the conducted parasitic heat loads.

3. Due to the nature of operation of Joule-Thompson coolers, the amplitude of any short period peak heat loads onto the coolers must be limited.

For both detector options, the following features are to be incorporated into the design in order to help meet the thermal interface requirements:

1. Passive disconnect systems: This system works by choosing a combination of structural support materials which have different coefficients of thermal expansion (e.g. Vespel SP22 and GFRP) and taking advantage of the temperature difference between launch and orbit. At launch, the main structural load between different temperature stages is supported by the GFRP. Once the instrument is in orbit at the operating temperature, the differential thermal contraction between the two materials creates a mechanical separation between the two thermal stages and achieves excellent thermal isolation through the Vespel.

2. Superconducting instrument harness: The use of NbTi harnesses for the mechanisms and the harnesses has two thermal benefits, firstly the parasitic heat load conducted into the instrument from the higher temperature stages is minimised due to the very low thermal conductivity of the superconducting wire, and secondly the ohmic dissipation in conductors carrying significant current is minimised.

Photoconductor Option

The photoconductor detector option requires the use of cold electronics to bias, readout and multiplex the optical signals. This gives rise to thermal loads on the cryogenic system from both the conductive heat loads along the harness as well as the ohmic dissipation in the electronic components. Two sub-options were investigated: one where the cold electronics were coupled to the 4.5K stage and one where the cold electronics were coupled to a higher, 20K stage. For each of these sub-options, it was found that the size of the arrays had to be limited in order to minimize the number of pixels and the resulting cryogenic heat loads. This would mean that the objective of a fully sampled, 3.8’x3.8’ field of view working in four wavelength bands would not be feasible from a thermal point of view. A modest set of small detector arrays would be feasible and could represent a low risk instrument solution from the thermal/structural point of view.
TES Option
Several different thermal architecture options capable of cooling the detector elements to 100-mK were investigated. The most promising in terms of interfacing to the Joule-Thompson cooler and in terms of mass is a system comprising a 3-He sorption cooler coupled to two ADR refrigerators. The design of the sorption cooler is adapted to enable it to interface with the 1.7, 2.5 and 4.5K stages of the satellite. It has also been adapted to minimise the peak heat flux onto the satellite during recycling of the sorption cooler. The two ADR stages are cascaded off the sorption cooler and are run in such a way as to provide 20 mW of cooling a constant base temperature of ~70mK to the detectors (the figure of 20 mW of cooling at 70mK is an initial estimate of the load from the detector arrays). The peak power load onto the 4.5K stage of the satellite during recycle would be limited to 10-15 mW. It should be stated that the cascaded Sorption cooler/ADR system is relatively complex and would require the use of around five heat switches operating at temperatures between 4.5K and 70-mK. The stability of the detector array base temperature could also be an issue.

6.4 Sampling and Telemetry
Which ever detector technology is chosen for the ESI, some fundamental parameters remain fixed for the operation of a raid scanning FTS. The speed of the mirrors, combined with the speed of response of the detectors, governs the audio bandwidth of the detected signals. If we assume that the detectors have a response frequency of 20 Hz, similar to the Herschel-SPIRE bolometers, then at the minimum and maximum audio frequencies will be ~2.5-20 Hz if we scan at the maximum allowed rate of optical path difference change of ~0.05 cm/sec. For the highest resolution in the FTS of 0.05 cm⁻¹ this requires about 280 sec per scan. In order to correctly sample the interferogram at this speed we need to have the following frame rates and consequent analog to digital conversion rates per pixel:

3 Band – 1 arcmin FOV
Band 1 – 80 Hz - whole array to be read in 12.5 msec ~2 µsec per conversion
Band 2 – 37 Hz - whole array to be read in 27 msec ~17 µsec per conversion
Band 3 – 21.5 Hz – whole array to be read in 46 msec ~ ~80 µsec per conversion

4 Band – 3.8 arcmin FOV
Band 1 – 80 Hz – array read in 12.5 msec ~ 0.2 µsec per conversion
Band 2 – 50 Hz – array read in 20 msec ~0.3 µsec per conversion
Band 3 – 33 Hz – array read in 30 msec ~1.1 µsec per conversion
Band 4 – 20 Hz – array read in ~50 msec 7.8 µsec per conversion

The conversion times for the largest array sizes are challenging for space qualified electronics. The fastest conversion rates currently available for 12 bit ADCs are perhaps 1.5 Msamples/sec – or ~ 1 µsec per conversion – and considerably slower for 14 or 16 bit ADCs. We have not as yet determined exactly how many bits are required in terms of direct digitization compared to using gain or offset controls to remove signal pedestals. It is clear however that the issue of sampling and conversion rates will have a significant impact on the ultimate number of pixels, and therefore the array sizes, whichever detector technology is chosen for ESI.

If we assume that we need ultimately to encode the signals to 16 bits per sample we would generate raw data rates of about 10 MBit/s for the 3 band option and up to 160 MBit/s for the 3.8 arcmin FOV four band option. The latter does not seem feasible given the need to keep the data rate to within an average of 2 to 2.5 MBits/s to fit within the link budget. We can envisage that a smaller field of view in at least the short wavelength bands would be required – perhaps 2x2 arcmin reducing the data rate to ~40 MBits/s. Onboard data compression techniques will be required and we will investigate this further during an Phase A study. The need for onboard data processing this will impact on the warm electronics architecture, probably requiring a dedicated signal processing unit.

7. Operations and Data Processing

7.1 Instrument Operations
The ESI is conceived as an instrument for dedicated pointed observations of individual fields. We expect that the ESI instrument will require the following operational modes with the SPICA satellite:

1. Pointed observations – long observations on a single point on the sky – with or without in field chopping using an internal chop mirror. Up to 30 minutes stationary pointing required with drift <0.5 arcsec (TBC) in 5 minutes, the length of a typical FTS mirror scan. Blind pointing ability will not be an issue assuming that the arrays spatially Nyquist sample and the pointing ability places a target within (say) 10% of the FOV to ensure the target is centrally placed.
2. Raster observations – these will be used to map areas of the sky larger than the instantaneous instrument field of view. These will consist of concatenated pointed observations of a fixed grid with perhaps the ability to return to an “off” position after a certain number of positions. The blind pointing at the first point in the raster will again not be an issue, but it is essential to be able to reconstruct the pointing of each pointing within the
raster map to less than the equivalent of the pixel at the shortest wavelength (<=0.9 arcsec) in order not to
introduce systematic noise into the reconstructed mosaics.
2. Nodded observations – a target of interest within the field may need to be “swapped” from one portion of
the array to another moving the telescope rather than any internal mirror if there is system level straylight or
other thermal backgrounds. This will allow us to subtract off any satellite induced background to achieve the
ultimate photometric accuracy.

The instrument modes for ESI are likewise straightforward with only a few operational modes:

1. Medium resolution scanning mode spectroscopy – the FTS mirror is scanned at maximum speed over the
full range of motion required for R≈2000 spectroscopy. The length of each scan will be of order of 300
seconds and at least two scans per pointing are required for data redundancy.
2. Low resolution SED mode spectroscopy – the FTS mirror is moved either in “step and look” or in scanning
mode over a range of motion to give R≈10-20. The length of each scan will be of order of 10 seconds and at
least two scans per pointing are required for data redundancy
3. High resolution FP mode spectroscopy – if a high resolution mode is finally designed into ESI this mode
will be employed. An interchange wheel will move the FP into the optical chain, the FP will be stepped over
the range appropriate for the wavelength(s) of interest and the FTS scanned over the range of motion required
to ensure order separation – R~ few hundred should be sufficient. This mode requires more detailed analysis
and it is far from certain that it can be included.
4. Photometric Chop or Stare Mode – with the mirror mechanism held stationary the ESI can be used as a
photometric camera, albeit with reduced throughput. In this mode the mechanism is “parked” and, if fitted, the
internal mirror will be used to chop on the sky.

Detailed power and telemetry budgets will be provided for each of these modes in the course of further study.

7.2 Data Processing and Operations Support
At this early stage of the project much is uncertain about the data processing and operations scenarios for the SPICA
mission; however, it is expected that the ESI consortium will provide data processing and analysis software as part of
the delivery of the instrument. It is also expected that the European consortium will be largely responsible for the in
flight operations of the instrument based on the experience gained during the ground test campaigns both at instrument
level and at integrated satellite level. Whether this will be by the provision of effort at the ground station (in Japan or
elsewhere) or b the provision of the offline effort to analyse flight data offline and provide flight operations scripts is a
matter of negotiation between the interested parties.

7.3 Instrument Testing and Calibration
Members of the ESI consortium have a long experience in developing cryogenic space instruments and have developed
and maintained much of the infrastructure and laboratory experience required to build, test and calibrate these
instruments. This equipment and experience would be available to the instrument consortium for the development of
ESI. In addition, the consortium would have access to several large test facilities within Europe to carry out the
qualification of the instrument.

8. Development Roadmap
This study has demonstrated that a conceptual design for an imaging FIR spectrometer is feasible for the SPICA
mission and will meet the scientific goals of the mission. However, in order to meet those goals there are certain critical
technological developments that must be demonstrated before commitment to the final detailed design of the instrument.
These must be shown to be feasible and affordable before the end of the Phase A study and, if they prove not to have
reached the right level of technical maturity, backup solutions based on less risky technology must be in place. The
latter may involve building an instrument with less performance or, more favourably, with less capability, than the goal
concept.

The most critical areas requiring technical study up to and including breadboard demonstrations are:

1. **Filled TES bolometer arrays working at wavelengths from 25 to 50 \( \mu \text{m} \)** – these offer the prospect of
high sensitivity large format “filled” arrays in a wavelength range not well covered by other technologies.
However, as discussed in this report, many challenges must be met if they are to fulfil this potential. By the
end of Phase A a small demonstration array must have been shown to meet the performance specification at
the proposed flight temperature with a high level of multiplexing. If we can demonstrate a filled TES array
working at the shortest wavelength band, the longer wavelength bands should only require scaling of the
technology.
2. **100 mK minature continuous ADR and sorption cooler working from a J-T cooler.** The other
technology that requires demonstration by the end of Phase A is to provide the temperatures required for the
TES array operation. We have proposed an elegant solution to this issue but a demonstration of all the links in the chain working together is essential to ensure success.

3. **35 – 60 µm photoconductor** arrays – the alternative to having filled TES bolometer arrays is to use photoconductors. As we have discussed, much of this technology has already been developed for the current generation of instrument. This technology requires some (difficult) scaling issues and the development of reliable low noise cold readout electronics to meet the challenges of ESI. However in one critical band there has been little or no development of photoconductors – 35-50 µm. Here we must develop and demonstrate a small array of photoconductor pixels – probably Ge:Be although other alternatives could be sought – if the photoconductor array option is to remain credible.

4. **Warm Electronics for TES Bolometer Arrays** – parallel to the development of a demonstration TES bolometer array we must develop and demonstrate that it is feasible to build low mass; low volume and low power drive electronics for such a large number of pixels.

A design and development plan for the development phase will be produced as part of preparation of the bid for further funding for ESI.