1 Scientific objectives and capabilities

1.1 Introduction

The main scientific goals for which the SPIRE instrument is designed are amongst the most prominent, and still unresolved, questions of modern astrophysics:

how and when did galaxies form? - the investigation of the statistics and physics of galaxy and structure formation at high redshift;

how do stars form? - the study of the earliest phases of star formation, when the protostar is still coupled to the interstellar medium.

Answering these questions requires the ability to carry out large area deep imaging surveys at far-infrared and submillimetre wavelengths, and the ability to follow up these systematic survey observations with spectroscopy of selected sources. The design of SPIRE has been tailored for these highest priority scientific aims of the FIRST mission. It will also provide the astronomical community with a powerful multi-purpose instrument, capable of addressing a wide range of scientific questions.

The instrument will exploit the unique advantages of FIRST, which cannot be matched by any other facilities:

(i) the low-emissivity 80-K FIRST telescope, which provides a much lower thermal background than could ever be achieved with any ground-based or airborne platform;
(ii) the complete lack of atmospheric emission in space (even at aircraft altitudes, the sky emissivity has an average value of about 20% in the FIR-submillimetre range);
(iii) the large amount of observing time: at least 30,000 hrs. (equivalent to 35-40 years of SOFIA operation);
(iv) access to the poorly explored 200-700-μm spectral range.

These advantages mean that the sensitivity of SPIRE for deep photometry and moderate-resolution spectroscopy is far better than that of any Earth-based facility. For example, to be competitive with SPIRE for deep surveys, SOFIA would need an instrument with several hundred times as many detectors - far more than could ever be accommodated in its focal plane. Similarly, SPIRE will be more than 60 times faster for mapping observations than the JCMT SCUBA instrument at 450 μm, and over 1000 times faster at 350 μm.

1.1.1 Scientific capabilities of SPIRE

Broad-band photometry: SPIRE has a three band imaging photometer which is optimised for deep surveys. Dichroic beam dividers separate three bands with nominal wavelengths of 250, 350 and 500 μm and a spectral resolution $\lambda/\Delta\lambda \approx 3$. Three detector arrays observe simultaneously in the three bands, providing full sampling of the same approx. 4-arcminute field of view with angular resolution determined by the diffraction limit of the FIRST telescope (18″ at 250 μm). The photometer performance parameters are summarised in Fig. 1.1(a). These sensitivity estimates are based on a conservative feed-horn array option for SPIRE: significant improvements (a factor of 2-3 in mapping speed) can be achieved through the use of filled absorber arrays which are now being developed, as described in section 2. Details of the instrument design and of the assumptions made in estimating the sensitivity are given in section 2.4.

FTS spectroscopy: SPIRE also contains an imaging Martin-Puplett Fourier transform spectrometer (FTS) operating between 15 and 50 cm^{-1} (200 - 670 μm). The spectral resolution is variable between 0.04 - 2 cm^{-1} (corresponding to $\lambda/\Delta\lambda$ = 20 - 1000 at 250 μm). The FTS was chosen over grating and Fabry-Perot options due to its suitability for both full spectral survey observations and imaging, and its flexible spectral resolution, all of which are important for the key science goals of FIRST. The SPIRE

FTS has a field of view of 2 arcminutes and is optimised for spectral surveys, the aim being to measure the complete spectrum as rapidly and sensitively as possible. The spectrometer performance is summarised in Fig. 1.1 (b) and (c) for line observations and low-resolution continuum observations, respectively. Details of the calculations and assumptions are given in section 2.4.

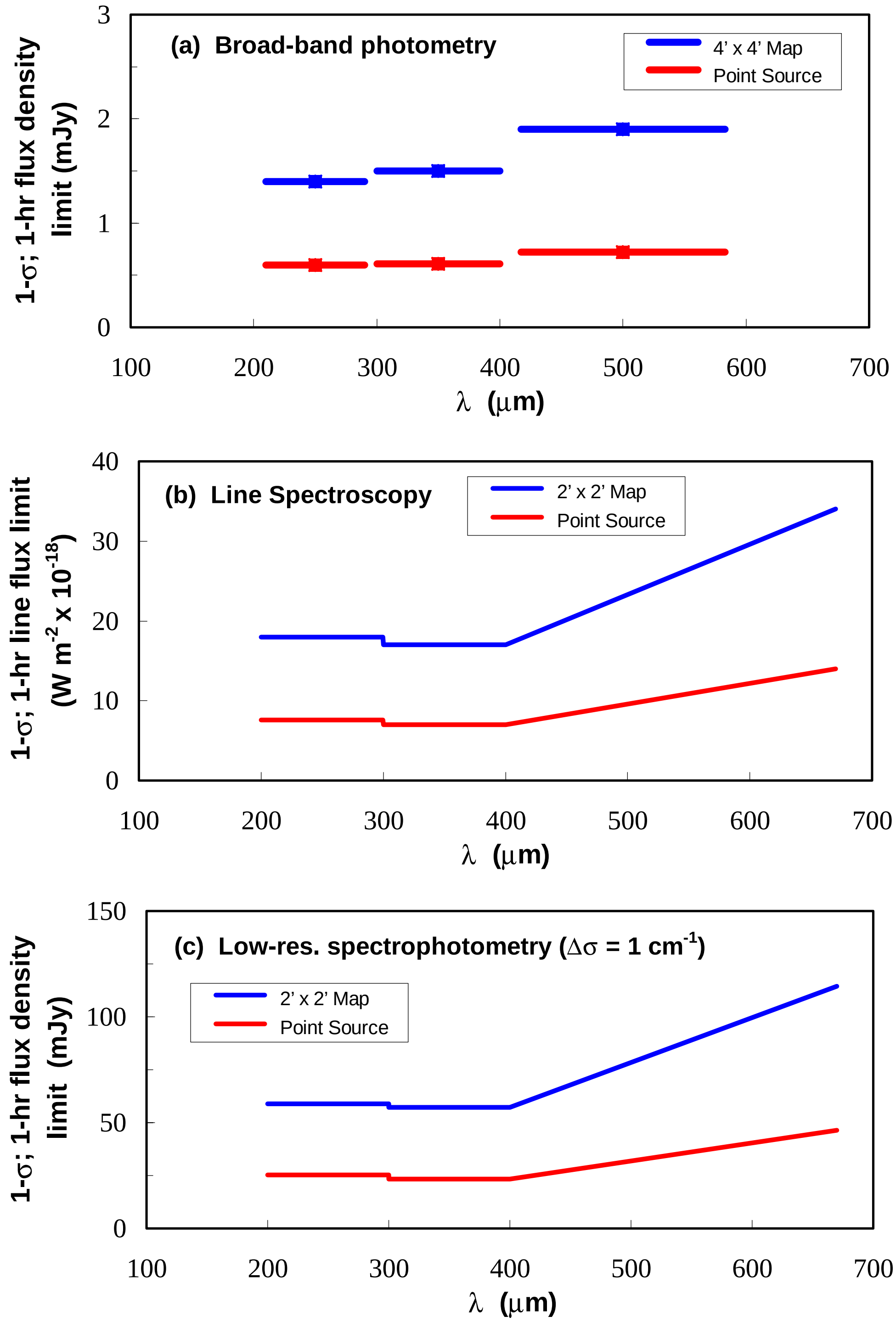

Figure 1.1: Estimated sensitivity of SPIRE for broad-band photometry, line spectroscopy and low-resolution spectrophotometry.

1.1.2 Scientific drivers for SPIRE

The scientific capabilities of SPIRE are tailored to probing the still poorly known wavelength region between 200 and 700 µm. Observations in this wavelength range are especially important for determining the history of star formation in galaxies and the early phases of star formation in the interstellar medium.

Since IRAS, it has been well known that galaxies emit most of their energy in this region. A large fraction (~ 30% for normal spirals to almost 100% for the most active ultra-luminous infrared galaxies) of the stellar emission is absorbed by dust and re-emitted in the far infrared. ISO has confirmed that dust in galaxies has temperatures in the range 20 - 30 K, with a corresponding peak emission between 60 and 150 µm. The peak is redshifted into the SPIRE wavelength domain for galaxies with redshift larger than ~ 1. The bolometric luminosity of a galaxy cannot be determined without an accurate measurement of the Spectral Energy Distribution (SED) in the far infrared. Despite considerable efforts, mainly based on observations with the HST and the Keck telescope (e.g., Madau *et al.*, 1996), the epoch of peak star formation in galaxies remains largely controversial, and is an issue which cannot be resolved without observations in the far infrared and submillimetre region, where the bulk of the emitted energy is to be found. Therefore, the study of the early phases of galaxy evolution at high redshift requires an instrument which can:

(i) detect the galaxies which emit in the far infrared and submillimetre;
(ii) determine their SEDs to derive their bolometric luminosity.

This is the main aim of SPIRE. It can be achieved by a large imaging survey in three bands, followed by low-resolution spectroscopic observations of a sub-sample of the detected objects selected according to photometric criteria.

Star formation results from the fragmentation and collapse of dense cloud cores in the interstellar medium. The main features of low-mass star formation and pre-main sequence evolution are relatively well understood (see, e.g., Shu *et al.*, 1987 for a review), but the very first stages of cloud collapse are still very poorly known. A global understanding of these phases is crucial, as they must eventually govern the origin of the stellar initial mass function (IMF). Recent ISO and ground-based submillimetre observations demonstrate that young protostars and pre-stellar clumps are cold (typically 20 K) and still opaque at 15 µm (e.g., André *et al.*, 1993; Abergel *et al.*, 1996). Sensitive observations at high spatial resolution in the far infrared and submillimetre region are needed to make complete surveys of such protostellar clumps to determine their bolometric luminosity and mass functions. The observational requirements are similar to the high-z galaxy surveys, but additional surveys at shorter wavelengths with FIRST-PHOC will be needed to measure the peak of the SED and to determine the dust temperature and emissivity.

These two highest priority programs call for an instrument with high-sensitivity continuum imaging capabilities in several bands to detect and make a first selection of interesting objects, and a low-resolution spectroscopic mode to obtain a detailed SED of selected objects. Most of these objects will be faint compared to the sky background, and accurate subtraction of the background must be performed. These scientific requirements have been important in the change from a grating spectrometer previously proposed for this instrument to an imaging FTS. The grating spectrometer has the disadvantage of a fixed spectral resolution not suitable for the faintest objects detected in the photometric surveys, and does naturally lend itself to providing an imaging capability.

In addition to meeting these aims, which rely on measurement of the continuum SED, SPIRE will give access to many important spectral lines. H_2O, which has been shown by ISO observations to be one of the major constituents of the interstellar medium, has many rotational lines in the SPIRE range. Several other diagnostic species, such as CO and CI, also have important transitions in this band. The FTS can measure the complete band in a single observation, providing a good measure of line ratios which are needed to determine physical conditions and abundances. The imaging capability of the FTS will enable astronomers to study how these lines vary with respect to the other physical conditions of the interstellar medium. The far infrared fine structure ionic emission lines, which are the main interstellar cooling agents, are predominantly in the FIRST-PHOC range, but fall in the SPIRE domain for redshifted objects providing an unprecedented capability of studying the physics of galaxies at high redshift.

The following sections describe some of the main scientific programs which SPIRE is expected to carry out. Although SPIRE has been optimised for the two main scientific programs, it will offer the astronomical community unique observing capabilities to tackle many other astrophysical problems: giant planets, comets, the galactic interstellar medium, nearby galaxies, ultraluminous IR galaxies, and AGNs. We are confident that, in the next 10 years, the capabilities of SPIRE will remain unchallenged by the ground based and the airborne observatories which are planned today.

1.2 Cosmological surveys with SPIRE

SPIRE will be used to make large area deep surveys for high-redshift galaxies. The main science drivers of the survey observations will be:

(a) To characterise the star-formation history in galaxies at z = 1-5, taking advantage of the unique capability of SPIRE to select preferentially distant galaxies due to the positive effect of the K-correction and the wide area covered by the survey.

(b) To investigate the existence of a population of high-z dusty star-forming galaxies missed by current (and future) optical and near-IR surveys - in particular, events associated with the formation of spheroids and elliptical galaxies. The existence of such a population would have strong implications for galaxy formation and for the star-formation history of the Universe.

(c) To investigate the formation and early evolution of AGNs and quasars, and to determine how massive black holes were formed in galaxy nuclei at high z. These events probably occurred during the early formation of spheroids, and probably in a dusty medium. The survey will provide a unique unbiased sample of Seyferts and quasars which will be ideal for testing unified schemes.

(d) To study large-scale structure in the high-redshift universe, providing crucial tests of structure formation scenarios. The photometric survey and the FTS spectroscopic follow-up will provide a crude photometric redshift classification of galaxies which can be used to study the clustering properties of these galaxies as a function of redshift.

Once high-z candidate galaxies and quasars are identified from the survey, follow-up observations with the SPIRE FTS and the other FIRST spectrometers will be the obvious next step for exploring the nature of the objects discovered. A concerted follow-up effort will also involve the proposed millimetre arrays, 10-m class ground-based telescopes, and NGST.

The submillimetre is clearly the critical band for studying high redshift galaxies. The exciting cosmological implications of exploring this region represents a unique prospect for the FIRST mission. In this respect, SPIRE surveys will provide a direct complement to the PLANCK survey which will measure the cosmological background fluctuations. PLANCK, by imaging the primeval plasma at $z \approx 1500$ will help to constrain the standard cosmological model and its associated parameters, while SPIRE will provide a direct view of the epoch of galaxy and large-scale structure formation over a substantially wide redshift interval

1.2.1 Star formation history of galaxies

One of the most exciting features of the FIRST mission will be the capability to measure the star formation history of the universe out to high redshifts. Indeed, such a measurement can only be made by FIRST, because a large fraction of the total power radiated by stars is re-emitted by dust in the wavelength range covered by SPIRE. There is a growing recognition that the importance of dust in the formation of stars locally extends out to the highest redshifts observed so far. The surveys and follow-up programmes carried out with SPIRE will be complementary to planned very large optical/near-IR ground-based and space observatories (VLT, Gemini, NGST), but without the view provided by SPIRE our picture of the star-formation history in galaxies will remain partial and incomplete. Figure 1.2 shows that the optical and near infrared SED a poor guide to what is happening at far infrared wavelengths, and the ratio of bolometric power in the far infrared and submillimetre to that in the optical and near infrared can range from 0.2 to 1000. Even in nearby starbursts, observations with ISO have demonstrated that the most intense star forming regions have large extinction (up to A_v = 70) and remain hidden from optical and UV observations (e.g.Mirabel *et al.*, 1998, and Fig. 1.6).

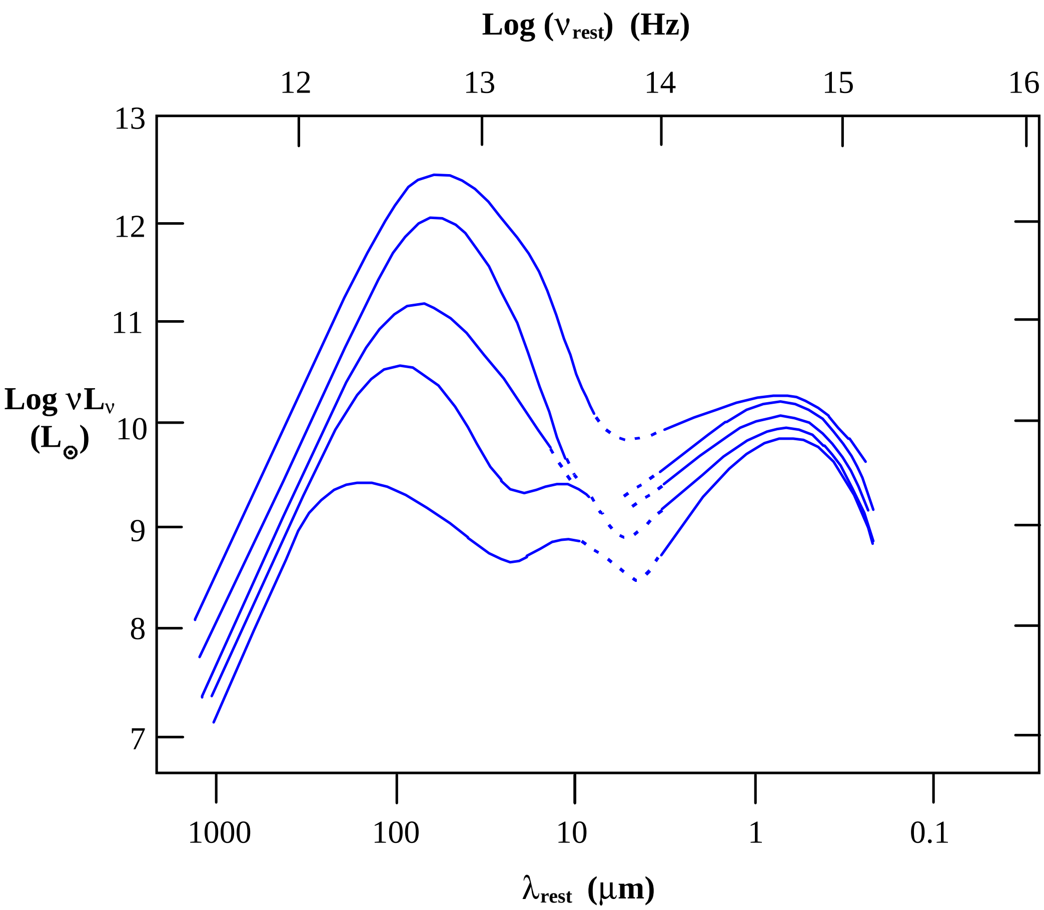

Figure 1.2: Spectral energy distributions of galaxies well-studied at far infrared wavelengths, demonstrating that the FIR/submillimetre spectrum is orders of magnitude more sensitive to the bolometric luminosity than the optical/NIR spectrum (after Sanders & Mirabel, 1996).

The history of star formation in galaxies remains a matter of intense debate. We have direct evidence at low z for strong evolution in the far infrared starburst population from IRAS redshift surveys. Strongly evolving rates of star formation are also seen out to z = 1 in ultraviolet galaxy counts from the Canada-France Redshift Survey (Lilley *et al.*, 1996), in the deep ISOCAM surveys at 15 μm undertaken by the CAM and ELAIS teams, including the Hubble Deep Field (HDF) (Oliver *et al.*, 1997; Aussel *et al.*, 1998), in the steep counts seen with ISOPHOT at 175 μm (Puget *et al.*, 1998), and in the sub-mJy radio population (Rowan-Robinson *et al.*, 1993; Hopkins *et al.*, 1998). The tentative detection of an isotropic submillimetre background radiation by Puget *et al.* (1996), recently confirmed by the DIRBE team (Hauser, AAS Meeting, January 1998) also supports the strongly evolving starburst scenarios (see also Schlegel *et al.*, 1997). Estimates of the star-formation rate at z = 2 - 4 from optical studies of the HDF are subject to very large uncertainties because of the unknown role of dust. Even the mid infrared observation by ISOCAM (Vigroux *et al.*, 1997) do not provide a direct determination of star formation rates. To provide an indication of the uncertainties of the present determination of the star formation history in galaxies, Table 1.1 gives the predictions of SPIRE source counts for a deep 60 sq. deg. survey for three different models, all of which are all compatible with the present observational constraints. Model A (Rowan-Robinson, 1998) has the minimum rate of evolution consistent with the

IRAS redshift surveys, the CFRS galaxy counts and the Madau *et al.* (1996) lower limits from the Hubble Deep Field; Model B (Franceschini *et al.*, 1997) assumes an additional population of high redshift starburst galaxies to account for bulge and elliptical galaxy formation; Model C (Guiderdoni *et al.*, 1998) involves even stronger evolution to account for the submillimetre background radiation. Corresponding numbers of sources expected in the survey, and the proportion of these with z > 1, are indicated in the table. The predictions of galaxy counts at 500μm differ by two orders of magnitude!

		λ (μm)		
		250	**350**	**500**
5-σ sensitivity (mJy)		15	16	20
Predicted number of sources	Model A	13300	3600	316
	Model B	70000	45000	9500
	Model C	70300	62200	27000
Percentage with z >1:	Model A	63	72	76
	Model B	41	55	59
	Model C	82	91	94
5-σ galaxy confusion limit (mJy):	Model A	10	12	9
	Model B	19	26	25
	Model C	19	26	30

Table 1.1: Typical parameters for a deep survey with SPIRE of 60 sq. deg. (assumed observing time for nominal sensitivites: 3000 hrs). Predicted source counts are given for three different models of galaxy formation and evolution, as described in the text.

Only deep surveys with SPIRE are capable of determining the role of dust in star-formation at high redshifts and hence the total rate of star-formation. Surveys with ISOPHOT can provide only a preliminary indication since their sensitivity is limited by confusion. The essential measurements will not be done by either SIRTF or SCUBA which can only bracket the critical wavelength range. Surveys with SIRTF (at 90 μm) and SCUBA (at 850 μm) will be capable of demonstrating the existence of a population of high redshift starburst galaxies, but will not be able to determine the bolometric luminosity and total star formation rate in these galaxies. A survey is not a realistic possibility with SOFIA given the much slower speed of observation compared to FIRST and the restricted amount of observing time per year with SOFIA. Similar considerations probably apply to the proposed 10-m submillimetre telescope at the South Pole.

Local starburst galaxies have their peak energy output at a wavelength of around 60-80 μm, and this is shifted to around 200 μm for the z = 2.3 hyperluminous galaxy IRAS F10214+4724 and to 350 μm for BR1202-0725 at z = 4.7. Since quasars are known with redshift close to 5, and already show evidence of significant heavy-element formation through emission lines and submillimetre emission from dust, the parent galaxies must be formed at redshifts greater than that, so z > 5 protogalaxies must exist. Figure 1.3 shows the spectrum of the nearby low-luminosity starburst galaxy M82, and a similar galaxy but assumed to be 100 times more luminous (3 x 10^{12} $L_\odot$,), at redshifts of 0.5, 1, 3, 5 and 10. The solid horizontal bars in Fig. 1.3 indicate the limit for a 5-σ detection by FIRST in 900 s integrations. A dusty galaxy of luminosity 3 x 10^{12} $L_\odot$ at z = 4 would be detectable at 5-σ in 900 s (the time per pointing of our baseline deep survey) by SPIRE, and one of similar luminosity at z = 10 in a 1-hour exposure (preferably at 500 μm). A massive forming galaxy with a few x 10^{11} $M_\odot$ is expected to easily produce such a luminosity, mostly reprocessed in the rest-frame far infrared (e.g., Franceschini *et al.*, 1994).

It will be a high priority for SPIRE to carry out a survey of a substantial area of the high-latitude, low dust column-density sky at wavelengths of 250, 350 and 500 μm. Such a survey could be carried out with a commitment of a modest fraction of the telescope observing time (roughly 20% over 2 years) and can be expected to yield thousands of galaxies, a high proportion of which would be at high redshift.

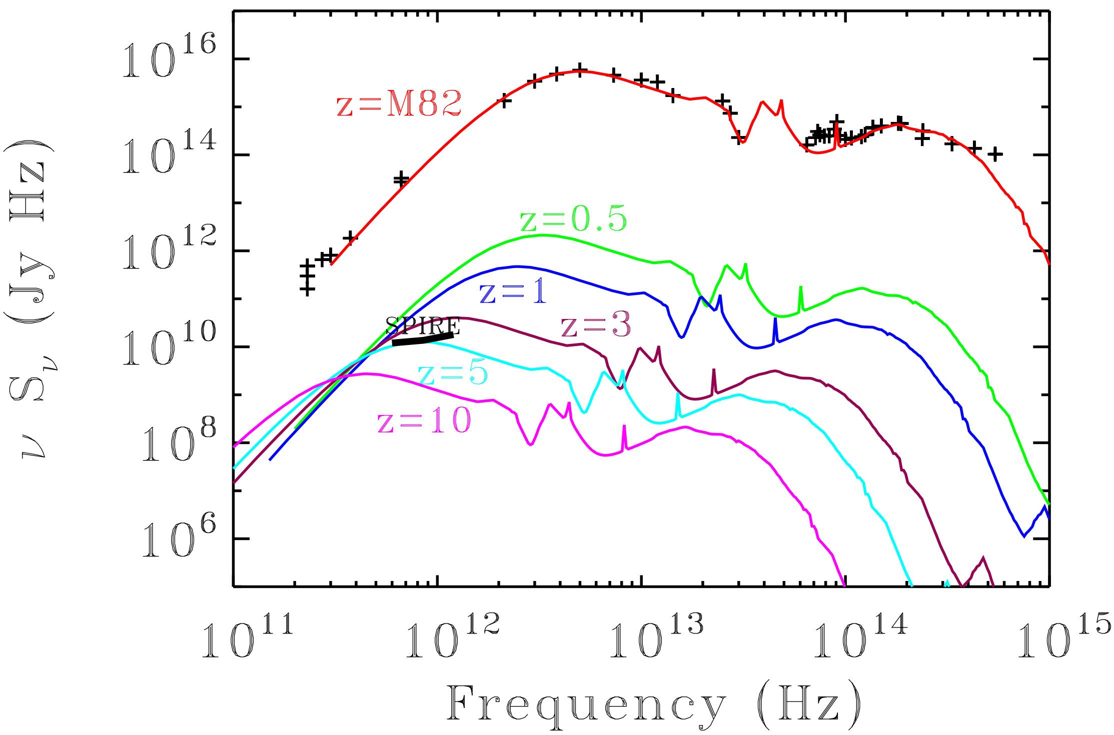

Figure 1.3: Spectral energy distribution for M82 and for a galaxy with a luminosity 100 times that of M82 (i.e., 3 x 10^{12} $L_\odot$) at a redshifts of 0.5, 1, 3, 5, 10. The horizontal bar shows the 5-σ sensitivity of a SPIRE 60 sq. deg. survey.

Given the uncertainty of the models, the survey must be large enough to detect a significant number of galaxies with redshift larger than 3. Taking the worst case, Model A of Rowan Robinson, a minimum size of 60 sq. deg. is needed to find a few tens of such high redshift galaxies (see Table 1.1). Such a survey could be done by SPIRE to a sensitivity of 15 mJy, slightly above the predicted confusion limit due to galaxies. The confusion due to Galactic cirrus or to galaxy clusters via the Sunyaev-Zeldovich effect is expected to be small. The calculation by Gautier *et al.* (1992) suggests that the 5-σ confusion limit due to cirrus for FIRST would be 0.5 mJy for wavelengths 200-1000 µm, for an assumed 100-µm intensity of 1.3 MJy/Sr. The area of sky selected would be chosen to be in the low dust-column sky as viewed in the IRAS and COBE maps. Predicted counts at the three survey wavelengths are shown in Fig. 1.4 for a range of evolving starburst models. Clearly, a survey of this scale would give significant numbers of high redshift star-forming galaxies and allow us to trace the star-formation history from z = 1 to 5. A large survey area will be crucial for investigation with high statistical precision of structure in the high redshift universe and of the correlation properties of distant galaxies. Knowledge of the galaxy distribution at high redshifts will provide an efficient probe to test models for structure formation.

It will also be of great interest to survey selected smaller areas to the confusion limit of FIRST with high signal-to-noise. Due to the uncertainties of the model predictions, an accurate determination of the confusion limit is of prime importance for the surveys. In addition, statistical analysis of the probability distribution of sky signals, P(D), can provide valuable information to a sensitivity well below the conventional confusion limit. A survey of 4 sq. deg. to a 5-σ limit of 6.5 mJy (about one hour per pointing) would take 1000 hours of observation. It will be valuable to survey the same areas of the sky with FIRST-PHOC in the wavelength range 85-200 µm, both to provide additional wavelength coverage for galaxy spectral energy distributions, and to permit more accurate positional determinations. Both deep and ultra-deep surveys would benefit greatly from the proposed filled-array detectors under development and the resulting total observation times for a given area of sky would be significantly reduced if these developments are successful. A substantial fraction of the sky will also be surveyed by PLANCK at 350, 550 and 850 μm, to a much shallower depth (5-σ = 130, 130, 63 mJy, respectively), and with a very much poorer resolution of 4.5 arcminutes. This will provide valuable complementary information to the FIRST surveys. Proposed ground-based millimetre arrays will be valuable in locating survey sources precisely for ground-based (or NGST) optical and near infrared follow-up.

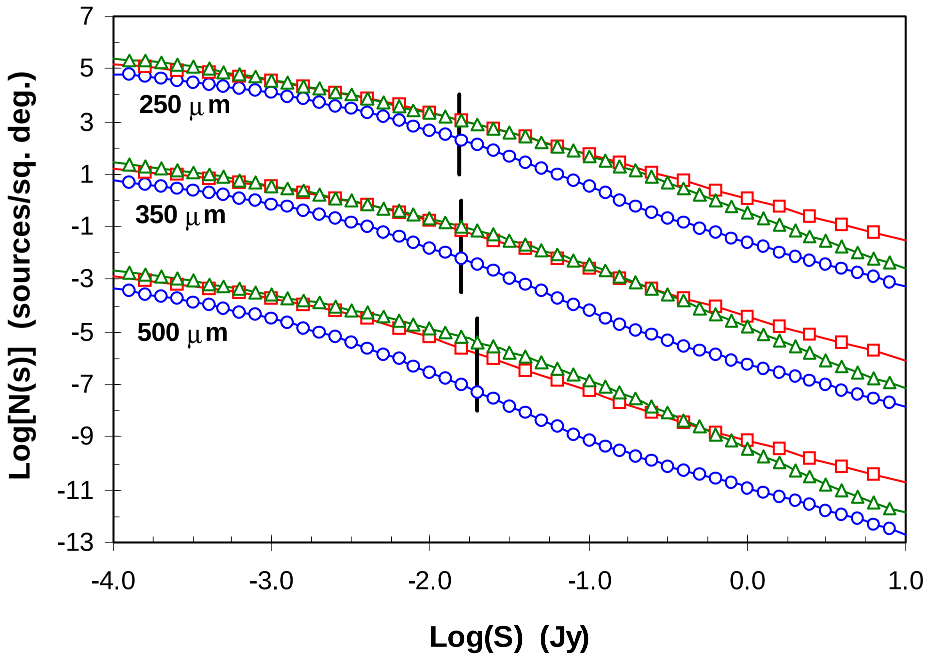

Figure 1.4: Predicted counts at 250, 350, and 500 μm for three models: Model A (blue, circles) is a minimal evolution model which fits the IRAS data and is consistent with lower limits from the HDF (Rowan-Robinson, 1998); Model B (red, squares) has an additional population of high-z starbursts to account for ellipticals and bulges (Franceschini *et al.*, 1997); Model C (green, triangles) is a strongly evolving model designed to account for the submillimetre background radiation (Guiderdoni *et al.*, 1998). For clarity, the curves for 350 and 500 μm have been displaced downwards by -4 and -8 in log(N), respectively. The vertical lines indicate the 5-σ sensitivity limits of the SPIRE baseline 60 sq. deg. survey.

Follow-up observations with the FTS at low resolution ($\Delta\sigma = 2$ cm^{-1}, corresponding to $\lambda/\Delta\lambda = 17$ at 300 μm) should yield basic information on the nature of the objects. The most interesting objects could be selected according to SPIRE colour criteria alone. A one-hour integration with the FTS would give a 5-σ sensitivity of around 60 mJy in the 200-400 μm range. The 60-μm peak of a typical starburst would fall in the FTS wavelength range (200-650 μm) for redshifts 2.3 - 8, so there is the exciting possibility of (approximate) photometric redshift estimation with SPIRE. The sensitivity limit of the FTS observations is only 2 - 3 times brighter than the sensitivity limit of the photometric survey. It will thus be possible to characterise a large fraction of the sources found in the photometric survey.

1.2.2 Detailed studies of high-redshift ultraluminous IR galaxies and quasars

Following the discovery of the z = 2.3 hyperluminous infrared galaxy IRAS F10214+4724, with a luminosity of 4 x 10^{13} h_{50}^{-2} $L_{\odot}$, after correction for the effect of gravitational lensing, over 20 such hyperluminous infrared galaxies and quasars have been found (Rowan-Robinson, 1996), with redshifts ranging up to 4.7 for BR1202-0725 (Omont *et al.*, 1996). These discoveries make it clear that dust can be formed at high redshift and that the total star formation rate cannot be estimated through ultraviolet and visible observations alone. By the time FIRST flies, hundreds of galaxies with z > 3 will have been found from ground-based surveys for Lyman dropout systems (Pettini & Bowden, 1997). It will be very interesting to study these, and the corresponding large samples of high redshift quasars and radio galaxies, at submillimetre wavelengths to search for evidence of starburst components. Figure 1.5 shows the far infrared and submillimetre spectra for the best observed of these, compared with a starburst model.

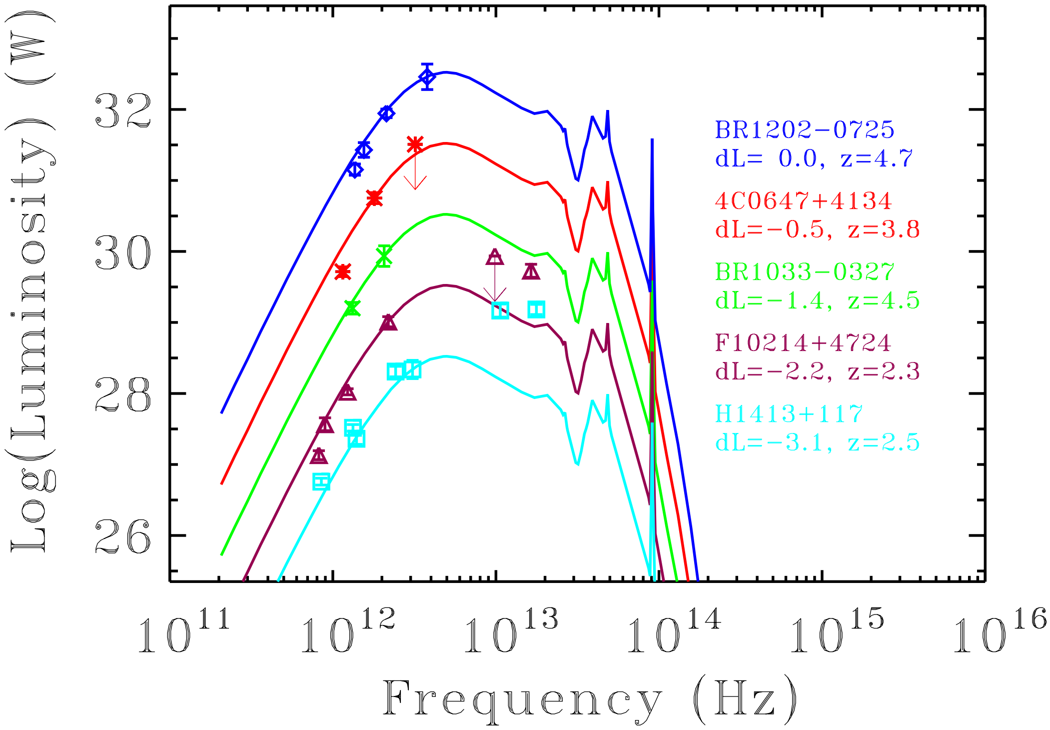

Figure 1.5: Rest-frame far infrared and submillimetre spectral energy distributions of high redshift (z > 2) galaxies and quasars with at least two submillimetre detections. The model curve in each case is the starburst model of Rowan-Robinson & Efstathiou (1993). The data have been shifted vertically by an amount dL for clarity.

In addition, a large number of such objects will be found in the SPIRE deep survey itself. SPIRE will reveal the details of the formation of galaxies and quasars, and will give insight into the evolution of the heavy element abundance through redshifted atomic lines, and the role of dust and molecules through redshifted dust features and molecular lines. It will be of great interest to compare the 10-100 µm spectra of nearby galaxies studied by ISO (and later by WIRE and SIRTF) with their high-redshift counterparts studied by FIRST. An important topic to be addressed by FIRST is the relationship between the formation of quasars and the formation of the parent galaxies in which they reside. A further question to which SPIRE will contribute significantly is the physical origin of the infrared emission from quasars - whether it is of non-thermal origin from the black hole or due to stellar processes. While some progress could be made for individual objects with SOFIA (assuming the development of a submillimetre photometer), the sensitivity of FIRST will be essential for statistical studies of significant samples of high redshift galaxies and quasars.

1.2.3 Active galaxies

IRAS and ISO observations provide excellent information on the far-infrared continuum and line emission from nearby active galaxies. In particular, ISO spectroscopy is showing the relative importance of active nuclei and starburst activity in ultraluminous IRAS galaxies (Genzel *et al.*, 1998). However those telescopes lacked the sensitivity to measure many galaxies at substantial redshifts. One product of SPIRE deep surveys will be a sample of active galaxies, selected purely on the basis of the submillimetre emission, which is isotropic and virtually unaffected by dust extinction, reducing the number of parameters that need to be invoked to explain their activity (Lawrence, 1997). Galaxies detected in the surveys will include high-z objects that are likely to be the younger counterparts of the IR ultraluminous galaxies selected at 60 μm by IRAS, (e.g. Lawrence *et al.*, 1986; Soifer *et al.*, 1987). The progress that the analysis of such samples will bring to galaxy and AGN evolution will be similar to that produced in cosmology from the study of IRAS selected galaxy samples. In addition, SPIRE will be able to measure the SEDs of active galaxies as a function of galaxy type and redshift. The SED has a cut-off at λ_{rest} > 150 μm which could be due to synchrotron self-absorption (non-thermal models predict a long-wavelength spectral index $\beta \leq 2.5$) or thermal dust emission ($\beta = 3.5 - 4$) (de Kool & Begelman, 1989). Using both the photometric and the low-resolution spectroscopic mode of SPIRE, the detailed shape of the turnover can be measured in a large sample of objects, and the relative importance of thermal and non-thermal emission processes in the far-IR continuum can be systematically investigated. SPIRE will also measure for the first time the submillimetre properties of radio galaxies, the supposedly misaligned parent population of BL Lac objects and radio-loud quasars. Their submillimetre properties should be orientation-independent but may or may not be very different from those of radio-quiet AGNs such as Seyfert galaxies. Measuring statistical samples of both normal and radio-galaxies will require sensitivities down to around 10 mJy.

Far infrared atomic and ionic fine structure lines (emitted in the 50 - 200-μm range) can be observed in active galaxies with high redshift. For example, at z > 1.3, the OIII 88-μm line, and at z > 2.2 the OI 63-μm line will be redshifted into the SPIRE range, allowing astronomers to derive the physical conditions of the dominant line emitting regions in intermediate to high-z objects. Scaling the line fluxes detected with the ISO-LWS in the prototypical Seyfert 2 galaxy NGC1068 (Spinoglio *et al.*, 1998), the OIII 88-μm line should be detected (S/N = 5 in 1 hr) in similar objects up to z = 1.6, while the OI 63-μm line up to z = 2.5.

1.3 Galaxies in the local universe

The study of the detailed dust properties in a wide range of nearby galaxies covering the Hubble sequence and range in star formation activities, is an area that will greatly benefit from joint SPIRE and PHOC observations. Understanding the rest-frame dust properties will provide diagnostic tools to study star formation and galaxy evolution in the early universe, a primary objective of FIRST.

1.3.1 The ISM in nearby galaxies

The SPIRE range has rarely been studied in nearby galaxies. Most of the submillimetre emission from galaxies originates from cold dust in the ISM. Recent ISOPHOT observations confirm that most dust in inactive galaxies is very cold - 10 K or less (Krügel *et al.*, 1998), while reanalysis of the COBE FIRAS data by Lagache *et al.* (1998) does not find the very cold dust component at 7 K in our Galaxy as originally suggested by Reach *et al.* (1995). The dust temperature in galaxies is a continuum, reflecting the gradual changes in excitation and density conditions ranging from a possible very cold dust component to a hotter phase consisting of grains in thermal equilibrium near high mass stars. If we are to use the dust energy output as a tracer of star formation, we must first understand the relationship between the detailed dust SED and the star formation process. For this, nearby galaxies represent an ideal laboratory as their proximity and the spatial resolution of FIRST will allow us to discriminate different physical regions inside galaxies.

Broad-band or low-resolution FTS maps of the SEDs of galaxies covering the Hubble sequence and a wide range of galaxy luminosity and mass, as well as a range of star formation activity, will provide unprecedented detail on the distribution of various phases of dust, each characterised by a particular temperature range and spatial distribution. The link between the dust and the other components of the ISM needs to be well understood, in particular how the dust components are related to the energy sources. This is of paramount importance to understand how the far infrared/submillimetre spectrum of a galaxy reflects its star formation properties. The links between the gas and dust can be explored with SPIRE, which will provide accurate determinations of dust masses. The long-standing question of why the Galactic gas-to-dust ratio is a factor of 10 higher than that measured in external galaxies

(Devereaux & Young, 1990), along with which parameters are responsible for variations, if any, can be resolved.

SPIRE will also study the molecular phase of galaxies, in a way that is complementary to the topics highlighted above. Aside from the lowest-lying CO transitions and HI, there is very little information on the physical characteristics and distribution of the gaseous components of the ISM in galaxies on global scales. Low-J CO lines are commonly used to trace molecular clouds of relatively low temperature and density, and are not sensitive to the hotter, denser gas in high- mass star forming regions from the more extended low-excitation gas. In contrast, the high-J CO lines provide us with a direct indication of where, in the molecular gas phase, does high-mass star formation occur now, as well as physical information on the excitation state of the gas, and therefore on the excitation sources (OB stars). The unique capability of the FTS will provide measurements of all of the CO lines in the range at once.

Water is expected to be a very abundant gas-phase constituent in molecular cloud cores, but the very determination of its abundance has been an outstanding problem in astrophysics. H_2O lines are inaccessible from the ground and even from airborne platforms. ISO has demonstrated that H_2O is ubiquitous in galactic molecular clouds and that it is also extended (van Dishoeck & Helmich 1996; Cernicharo, 1997). Water has also been detected in absorption towards Arp220 (Fisher *et al.*, 1997). The SPIRE range includes the fundamental transitions of ortho- and para-water. Its sensitivity and spatial and spectral resolution offer the exciting prospect of mapping the water lines in galaxies.

CI fine-structure lines are also vital diagnostic tools to probe the chemical and physical conditions of the ISM, but have only been detected in a handful of galaxies to date, mainly due to poor atmospheric transmission, even for an airborne platform. CI is proving to be one of the few reliable tracers of H_2 mass in the ISM where CO is not present (Keene*et al.*, 1997; Gerin & Phillips, 1997).

Such studies on a wide sample of nearby galaxies would allow the construction of accurately calibrated tools to interpret the far infrared and submillimetre spectrum of less resolved objects (both spatially and spectrally). They will also be complementary to those performed in the ISM of our own galaxy. By observing individual regions, one has precise detail of the physical phenomena at work in this region of the spectrum, but only by studying galaxies can one understand which of these phenomena dominate on large scales. Other galaxies can provide extreme environments that cannot be found in the Milky Way.

1.3.2 Dust cycling in the extragalactic ISM

Understanding of the most diffuse part of the ISM, or even intergalactic medium (IGM) requires better knowledge of the mechanisms involved in the survival of dust in the ISM, its transport and finally the possible formation of dust in the ISM/IGM. Establishing the timescales involved in the dust life cycle is essential to account correctly for its importance during the first phases of star formation, and nearby galaxies can provide strong constraints on these lifetimes. SPIRE will investigate the existence and importance of galactic halos and the true extent of the dust in disk galaxies. Dust has already been observed in the halos of nearby galaxies (e.g., Hughes *et al.*, 1994; Howk & Savage, 1998). It is not clear why the dust is present so far from the disk (up to 1.5 kpc) as current theories predict that little dust should survive in the expelled material. Determining how much dust is in the galactic halos will strongly constrain both our dust models and the mechanisms that eject material above the galactic planes.

Related to this is the possible detection of dust in the intracluster gas by IRAS (Wise, 1993) and ISOPHOT (Stickel *et al.*, 1998). Dust is not expected to survive in the IGM because electrons from the hot gas should easily destroy it through sputtering; but the gas is also extremely diffuse and little is known about the actual efficiency of the process. The presence of dust in the IGM of nearby clusters could be investigated with PHOC and SPIRE together, providing an unmatched combination of both sensitivity and resolution necessary to remove the contribution from galaxies. Measuring the mass of dust in the IGM of clusters would put constraints on the IGM enrichment mechanisms and have a strong bearing on our understanding of cluster evolution.

The BOL will allow us to complete the picture of the ISM in elliptical galaxies by tracing the abundance and distribution of the cold dust. The presence of cold dust has been confirmed in several elliptical galaxies (e.g., Wiklind & Henkel 1995). However, as the emission is intrinsically weak, it can only be studied in enough spectral and spatial detail from space. Determining the character and distribution of the dust in these galaxies provides insight into their history. It is currently thought that elliptical galaxies are the end products of mergers that have undergone strong starburst activity. By tracing various dust components in detail in these galaxies, it will be possible to differentiate a stellar mass loss origin for the dust (that following the stellar distribution), versus a remnant dust component originating from the pre-merging galaxies.

SPIRE can also address the long-standing question of the fate of gas in cooling flows. Today, given the numerous non-detections, the commonly accepted fate of this gas is that it forms low-mass stars. But the densities expected toward the centre of the cooling flows are also such that dust may form in-situ. Alternatively, low-mass stars could lose mass and generate dust. By comparing the SEDs of elliptical galaxies with and without cooling flows, SPIRE could put very tight constraints on the dust mass that is present in the central part of the cooling flow and ultimately on its star formation rate.

1.3.3 Galaxy interactions and nuclear activity

Galaxy interactions trigger central activity, such as starbursts and/or AGNs, and merging is a common occurrence in the formation and evolution of galaxies at high redshifts. Understanding mergers in the local universe will help the interpretation of the unresolved sources obtained from the FIRST cosmological survey. The high spatial resolution of FIRST will provide the opportunity to observe in detail the effect of individual components of the system during different stages of collision, and to observe the process of galaxy merging propagating throughout the entire system, in a similar fashion as ISOCAM does for the much hotter dust (Fig. 1.6). It might be expected that most of the dust is destroyed in the starburst due to the large number of supernovae (Greenhouse *et al.*, 1997). Observations of individual interacting galaxies covering a range of ages will allow astronomers to follow the fate of the dust and determine whether merging can lead to present day elliptical galaxies.

Investigating the nature of the heating source of AGNs also important. Complete coverage of SEDs using the low resolution FTS is vital to address this question. ISO data show convincingly that mid- and far infrared spectroscopy gives unique information on the physical processes and energy production mechanisms of AGNs and starbursts (Vigroux *et al.*, 1996 and Genzel *et al.*, 1998). For active, starburst and IR-ultraluminous galaxies, ISO spectroscopy has revealed the importance of molecular transitions in few template objects such as Arp 220, whose far-IR spectrum is dominated by absorption lines of OH, H_2O, CH, and NH_3 (Fischer *et al.*, 1997). For such galaxies, the SPIRE FTS spectral range includes many lines from CO (J = 4 - 3 through 13 - 12), CS, HCN, HCO^+, and H_2O, including the fundamental transitions of both para- and ortho-H_2O, allowing for the first time the detailed physical study of the ISM in the extreme conditions of their nuclear regions, characterised by high extinction and violent star formation bursts occurring in high density regions. Similarly, FTS spectroscopy of samples of obscured active galaxies, like Seyfert type 2 galaxies, will provide powerful probes of the presence of the molecular torus around the central engine.

Probing deeper into the AGN, SPIRE will help deciphering the nature of the emission through variability studies. Dust emission from low-z AGNs is not variable, but a class of AGNs, BL Lac objects and Blazars, have far infrared and submillimetre spectra which are dominated by non-thermal (synchrotron) emission. The submillimetre emission arises in the most compact core of the relativistic jet in these sources, and flare events are seen first at these wavelengths, providing a test of the predictions of shock models in the earliest stages, which has not been possible to date (e.g., Marscher & Gear, 1985). These regions are also considered to be the sources of X-ray and gamma-ray emission through the synchrotron self-Compton process. Submillimetre and X/γ-ray variability should therefore be correlated and comparison between the two spectral regions can constrain the detailed physics of models. SPIRE will be able to carry out variability studies with a photometric sensitivity and stability much better than that which can be achieved from the ground.

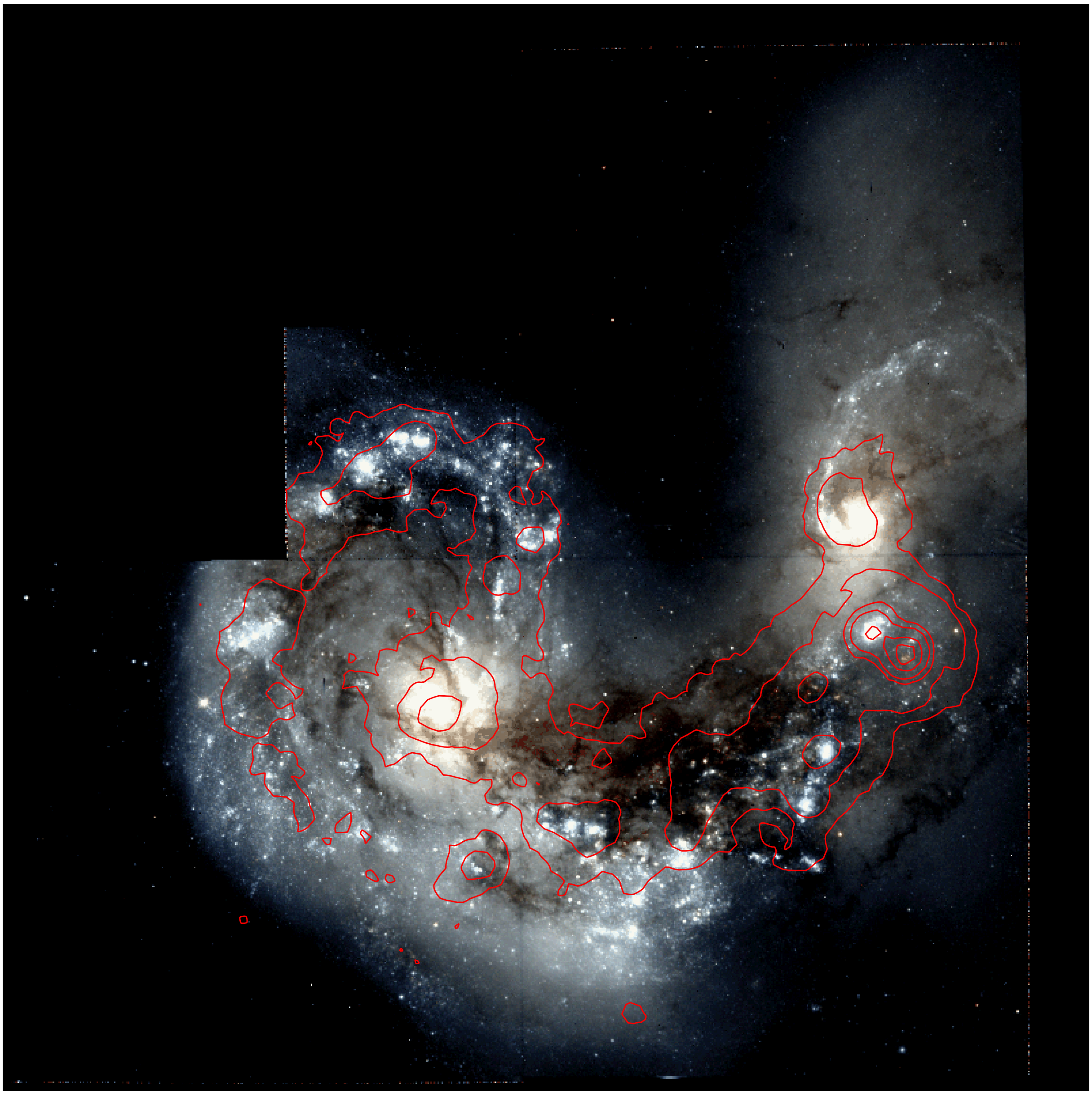

Figure 1.6: An overlay of the 15-µm ISOCAM emission of the Antennae galaxies on a combined V and I HST image. 15 % of the MIR emission originates in a point source that only has a very faint optical counterpart, while the overlap region between the two galaxies provides 50% of the total MIR flux (Vigroux *et al.*, 1996; Mirabel *et al.*, 1998).

1.3.4 Nearby low-metallicity galaxies as models of primeval galaxies

Aside from the global approach to the formation and evolution of galaxies that deep surveys bring, detailed studies of galaxies in early evolutionary stages will also be invaluable. Primeval galaxies are thought to be associated with a population of dwarf galaxies undergoing brief bursts of star formation. The active star-forming regions within dwarf irregular galaxies at $z > 1$ are also proposed to provide the bulk of the physically associated faint blue sources in the HDF (Colley *et al.*, 1997). Since blue compact dwarf galaxies are of low metallicity and contain very young HII regions (see, e.g., Thuan *et al.*, 1997), they could be regarded as local counterparts for the study of primeval galaxies. Studying them will therefore greatly assist the interpretation of high-z galaxy surveys with FIRST.

Local dwarf galaxies have undergone little chemical evolution, and so can provide unique insight into the relationship between the dust abundance and the ISM metallicity. Although they have metallicities that can range from 1/50 to 1/3 solar, many, including the most deficient ones, have been shown to harbour dust. A survey of dust continuum emission from dwarf galaxies covering a range of metallicities will determine whether the dust abundance scales with different heavy element abundances, thus providing information on the origin of dust. Different origins (e.g., from supernovae or AGB stars) would lead to different timescales for the formation of dust in galaxies. This is important to model deep number counts as it could allow for a significant dust-free phase of star formation in primeval galaxies.

These studies require high spatial resolution, high sensitivity and adequate sampling of the SED. SIRTF with its smaller telescope does not have good enough angular resolution and will not will cover the full range of the Rayleigh-Jeans regime necessary to differentiate various components. SOFIA can meet the spatial resolution requirement, will not match the sensitivity of SPIRE on FIRST. The 850-μm band of SCUBA, the only band with sufficient sensitivity to contribute to these studies, can reveal the presence of cold dust, but spectrophotometry over the range covered by PHOC and SPIRE is required to characterise the nature of the dust components. Building samples of significant sizes covering different galaxy types also requires the high observing efficiency of FIRST.

1.4 Protostars and young stellar objects (YSOs)

Understanding star formation on both small and large scales is a major unsolved problem of modern astrophysics. On the one hand we would like to know how the Sun and the solar system formed, and on the other hand global aspects of star formation have an important bearing on cosmology and the theory of galaxy formation. Since young protostars and pre-stellar cloud cores emit the bulk of their luminosity around wavelengths of 100-300 μm, FIRST is ideally suited for studying the earliest stages of star formation, which are particularly poorly known. Wide-field SPIRE imaging surveys at 250-500 μm will allow us to take a complete census of both protostellar and pre-collapse clumps in active and quiescent regions of nearby molecular clouds down to sub-stellar masses. Combining these surveys with co-ordinated PHOC mapping at 90 and 180 μm, it will be possible to determine the temperature structures and bolometric luminosities of all detected clumps. This is virtually impossible from the ground. As explained in section 1.4.1 below, such broad-band surveys will tremendously improve our knowledge of both individual and global star formation in the Galaxy. Follow-up spectroscopic studies will greatly help to constrain the nature of the most interesting sources (see section 1.4.2).

1.4.1 Broad-band protostellar surveys of active and quiescent molecular clouds

Formation and evolution of individual protostars: Wide-field imaging surveys of nearby molecular clouds with SPIRE will be a powerful tool to investigate the first phases of protostellar collapse. These are poorly understood, partly because the associated timescales are short (~ 10^4 yr.), and partly because the corresponding SEDs peak in the 100-300 μm range - i.e., in the primary wavelength range of FIRST which has been inaccessible with good resolution and sensitivity up to now. IRAS, ISO, and ground-based infrared studies have provided a fairly complete census of evolved protostars and pre-main sequence objects in nearby clouds, in the form of Class I, Class II, and Class III near-IR sources (e.g., Lada, 1987). But no such census exists yet for young (Class 0) protostars at the beginning of the main accretion phase (e.g., André *et al.*, 1993), for isothermal collapsing protostars (e.g., Larson, 1969; Mezger *et al.*, 1992), and for cold pre-collapse clumps (e.g., Ward-Thompson *et al.*, 1994). At these early protostellar stages, the SED resembles a cold submillimetre blackbody at T ~ 10-30 K (see Fig. 1.7). Only a few candidate isothermal protostars have been identified and all remain controversial (Mezger *et al.*, 1992; Motte *et al.*, 1998). Likewise, there are only about twenty Class 0 protostars known to date (e.g., André, 1996), which all are relatively massive ($M > 0.5\text{-}1\ M_\odot$) and were discovered either serendipitously (e.g., Chini *et al*, 1993) or through their powerful outflows (see Bachiller, 1996).

By making unbiased continuum surveys for dense cold clumps down to much smaller masses ($M < 0.03\ M_\odot$) than is possible from the ground, SPIRE can, for the first time, detect complete samples of young protostars, comprising hundreds of objects (see below). This will provide reliable statistical estimates for the lifetimes of the isothermal and Class 0 protostellar phases in a variety of star-forming regions, and for the whole spectrum of stellar masses.

A second, unique contribution of SPIRE will be the determination of accurate luminosities and temperatures for protostellar sources, but for this purpose complementary imaging with PHOC will be required. Most of the luminosity radiated by a protostar at any stage lies in the range 100-300 µm. Unfortunately, due to the poor angular resolution of IRAS or ISO in the FIR, the emission of protostars embedded in clusters - even nearby such as ρ Ophiuchi - is totally unknown between 60 and 300 µm. Consequently, our current estimates of protostellar bolometric luminosities in clustered regions suffer large uncertainties, even in the case of Class I objects (Wilking *et al.*, 1989). The angular resolution of the complementary PHOC surveys (~ 6" at 90 µm) will be sufficient to separate the main individual members of nearby (< ~ 900 pc) embedded clusters. For the first time, the energy output of many individual protostars will thus be measurable in the key 90-300 µm range (see Fig. 1.7). This is of crucial importance as the bolometric luminosity is a fundamental variable of (proto)stellar astrophysics used in all evolutionary diagrams proposed to date for embedded YSOs (e.g. Saraceno *et al.*, 1996).

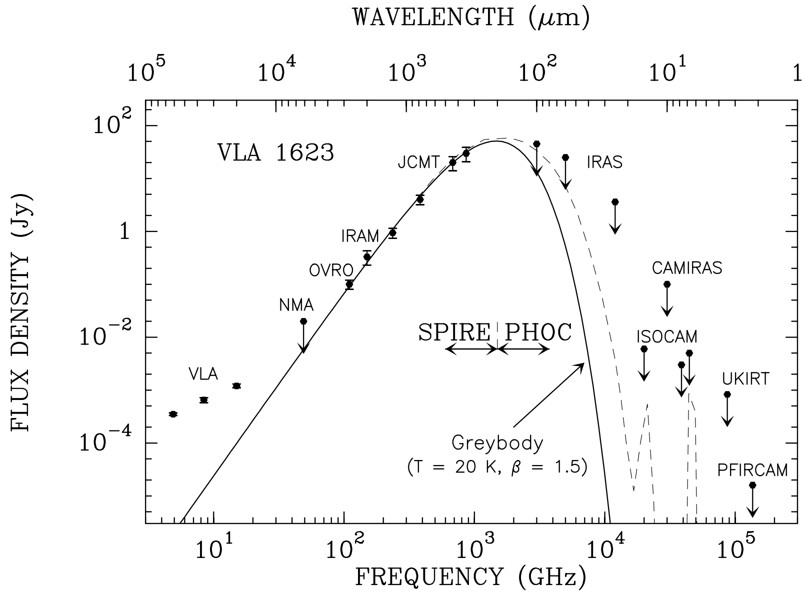

Figure 1.7: SED of the prototype Class 0 protostar VLA1623, with a grey body fit and a radiative transfer model fit. This object is at d = 160 pc, and has $L_{bol} \approx 1\ L_{\odot}$, $T_{proto} \approx 20$ K, and $M_{proto} \approx 0.7\ M_{\odot}$. The (10 σ , 1 hr) sensitivity of SPIRE/PHOC is indicated for comparison. SPIRE is ideally suited for taking a census of such cold protostars to $M_{proto} \approx 0.03\ M_{\odot}$ in the Galaxy.

Using co-ordinated SPIRE and PHOC observations to construct colour-colour dust continuum maps around λ ~ 200 µm (around the peak of protostellar SEDs), it will be possible to derive the temperature structure of both protostars and pre-stellar clumps/cores. This will allow us to determine the extent to which the envelopes of accreting (Class 0 and Class I) protostars are being internally heated, and whether pre-collapse cloud cores - presumably externally heated - are isothermal or colder in their inner regions (see Falgarone & Puget, 1985). Combined with complementary ground-based observations in the submillimetre continuum, the column density structure of the same sources will also be measurable with unprecedented accuracy. Promising results have been obtained in this area using JCMT/IRAM 800-1300 µm emission maps and ISOCAM mid-IR absorption maps (e.g., Ward-Thompson *et al.*, 1994; Abergel *et al.*, 1996). However, the only way to reach unambiguous conclusions is to constrain the temperature and the column-density gradient simultaneously through multi-band imaging from the Rayleigh-Jeans part of the emission spectrum up to and beyond the peak of the SED. Comparison between the structure of pre-stellar clumps and that of young protostars will give insight into the initial conditions of individual protostellar collapse. Follow-up, low-resolution (R = 20) spectral imaging with SPIRE will be very helpful to refine the photometric SED results on selected sources (see section 1.4.2 below).

Global aspects: origin of the Initial Mass Function (IMF): Wide-field SPIRE imaging of both active and quiescent regions should also allow us to better understand the origin of stellar masses and the nature of the fragmentation process in molecular clouds, for which we still have no satisfactory theory (e.g., Falgarone *et al.*, 1991). Sensitive submillimetre dust emission maps have the remarkable property that they can probe cloud structure, pre-collapse clumps, collapsing and accreting protostars, and post-collapse circumstellar envelopes/disks, *simultaneously* (e.g., Motte *et al.*, 1998). Thus, they make it possible to study the genetic link between pre-stellar dense clumps and young stars. In particular, the large-scale surveys envisaged with SPIRE (see Feasibility below) will allow us to derive the mass spectrum of pre-stellar clumps in the mapped clouds. At the same time, combining SPIRE and PHOC images with existing near-IR and mid-IR data (e.g. Nordh *et al.*, 1996) will give us access to the YSO bolometric luminosity function in the same clouds. The latter will constrain the mass spectrum of protostars and YSOs. It will therefore be possible to relate the mass spectrum of pre-collapse clumps to the mass spectrum of young stars, which will provide insight into the origin of the IMF. A preliminary comparison based on an extensive 1.3-mm continuum map of ρ Ophiuchi (Motte *et al.*, 1998) suggests that the mass distribution of small pre-stellar clumps (0.01-0.02 pc, equivalent to 15-30" in ρ Oph) mimics the Salpeter stellar initial mass function (IMF) above ~ 0.5 $M_\odot$, i.e., it is consistent with $dN/dm \propto m^{-2.5}$. These 1.3-mm pre-stellar clumps may thus be the direct progenitors of individual stars. SPIRE surveys will probe much deeper into the mass distributions of clumps and YSOs than ground-based (sub)millimetre studies. Furthermore, the mass uncertainties will be much reduced, especially if co-ordinated PHOC observations are available to fully constrain the temperature and emissivity of the dust, as well as the nature of the clumps. In this way, SPIRE will provide a unique method of investigating the low-mass tail of the IMF (for M < 0.1 $M_\odot$) and of searching for proto-brown dwarfs (defined as self-gravitating dense clumps less massive than the hydrogen burning limit of 0.08 $M_\odot$).

Large-scale surveys of molecular clouds with SPIRE (and PHOC) will also provide direct estimates of the associated star formation rates. The instantaneous star creation rate *C* of a cloud is simply related to its total number of (short-lived) protostars, N_{proto}, by $N_{proto} \approx C t_{proto}$, where t_{proto} is the characteristic protostar lifetime. Both N_{proto} and t_{proto} can be estimated as a function of stellar mass using the results of complete SPIRE/PHOC surveys. Estimating *C* in this way for the local Galactic neighbourhood would be particularly valuable as most present derivations are based on estimates of the formation rate of massive stars and require an independent assumption about the IMF (e.g., Güsten & Mezger, 1983).

Feasibility and uniqueness of SPIRE surveys: There are about 20 large molecular complexes within 1 kpc of the Sun (e.g., Dame *et al.*, 1987), the closest and most famous of which being the ρ Ophiuchi, Taurus, Chamaeleon, Corona Australis, Serpens, Perseus, and Orion dark clouds. These giant complexes harbour several compact embedded clusters which contain large, homogeneous samples of YSOs and protostars, and thus provide ideal laboratories for star formation studies. Since the details of the star formation process appear to vary from cloud to cloud and to depend on environmental factors, it is crucial to study a large number of the above regions in order to build a complete theoretical picture. Based on current estimates of the local star formation rate (~0.02 $M_\odot$ $yr.^{-1}$: Güsten & Mezger, 1983), these nearby regions should harbour > 500 young low-mass protostars - an order of magnitude more at least than those already identified from the ground. In addition to active clusters, it would be highly desirable to map *quiescent* regions, in order to investigate the factors that control the efficiency of star formation in molecular clouds.

One will need ~ 3 days to survey 1 $deg.^2$ with SPIRE down to the 10-σ 250-μm sensitivity of ~ 30 mJy required to detect proto-brown dwarfs of temperature $T_{proto} = 10\ K$ and mass $M_{proto} = 0.03\ M_\odot$ at the distance *d* = 450 pc of Orion, the nearest GMC. About 1 month of spacecraft time would be sufficient to survey, with adequate sensitivity at 250μm, most known active regions within 1 kpc of the Sun, as well as a comparable area in quiescent fields of nearby GMCs (i.e., a total area of ~ 50 $deg.^2$). This is 2-3 orders of magnitude faster than SCUBA at 850 μm and competitive with the planned MMA/LSA at 1.3 mm. More importantly, surveys by FIRST and by the MMA would be highly complementary: while the latter will give access to the small-scale structure and kinematics of protostellar clumps, the former will provide unique information about luminosities and temperatures.

1.4.2 Spectroscopic studies

Follow-up of the photometric surveys: The spectral imaging capability of the FTS together with its spectral resolution (up to 1000) will provide a very useful tool to better characterise the nature of the most interesting protostars and dense clumps found by the photometric surveys. Adapting the spectral resolution (R = 20 to 1000) to the source strength, the SPIRE FTS will provide measurement of the complete shape of the dust continuum spectrum from 200 to 650 μm for most protostellar clumps. Variations of the dust spectrum over this wavelength range will be measurable in the 2 x 2 arcminute field of view and will give fundamental information on likely changes of grain emissivity and/or temperature within and around protostellar clumps. Using the best possible spectral resolution it will be possible to measure any atomic CI line which might be present, together with molecular lines (CO and H_2O) which are expected to dominate the cooling in collapsing protostellar envelopes (Ceccarelli *et al.*, 1996). This will give important insight into the physical and chemical properties at the onset of protostellar collapse. As the atomic and molecular lines are expected to be narrow, any line detection with SPIRE will be followed up by dedicated HIFI measurements at higher spectral resolution in order to constrain the associated velocity fields, e.g., rotation, outflow or inflow.

Spectroscopic study of YSOs and their outflows: Outflows from protostars are known to play a central role in star formation, e.g., by dissipating the angular momentum of the infalling materail (e.g. Shu *et al.*, 1987; Bachiller, 1996). The FTS range includes transitions which probe of the physics and chemistry of the shock-excited molecular gas, and are ideal for studying molecular species like CO and H_2O which dominate the cooling of the gas, as shown by recent ISO-LWS results (e.g., Saraceno *et al.*, 1997). The CO high-J rotational lines, in particular, appear to be the best tracers of the mass and the temperature of shocked gas along the outflow and within the inner warm stellar envelope. As shown in Fig. 1.8, analysis of CO emission as a function of rotational quantum number shows that the peak of the distribution is at wavelengths longer than covered by ISO (Nisini *et al.*, 1997). The FTS will allow this emission to be detected and spatially mapped; moreover, comparison with submillimetre lines observed from the ground shows the presence of gas components at different temperatures, which can be disentangled in the spectral gap between ISO and ground-based telescopes: the SPIRE range.

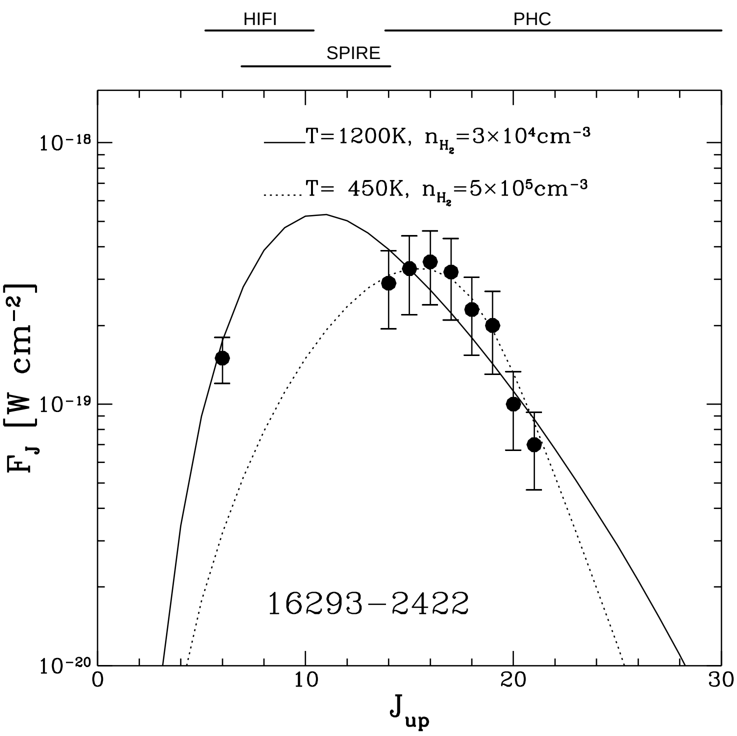

Fig. 1.8: CO line fluxes observed by the ISO-LWS as a function of rotational quantum number, J_{up} for the young Class 0 protostar IRAS16293-2422 (Ceccarelli *et al.*, 1998). The ground-based observation of the CO(6-5) line is also shown. The solid and dotted lines are best-fit models through all the CO lines and through the transitions observed by ISO, respectively.

SPIRE can cover with a single full spectrum all the lines from J = 7 to 13 with much higher angular resolution than ISO, and can spatially map of these lines in a large number of outflows from sources in different evolutionary phases, thus allowing a first statistical study of the phenomenon. It will also be able to map the distribution of water vapour through the fundamental para and ortho transitions of H_2O and its isotopes, allowing the change in the water abundance in the circumstellar environment to be related to the evolutionary stage. If the gas is sufficiently warm to excite transitions in the SPIRE range, the FTS can also map the distribution within outflows of several molecular species like SiO, HCN, and CN, which have strongly enhanced abundances in the warm shocked gas (Bachiller, 1996). From this it will be possible to discriminate between different shock models. Imaging the 200- to 670-μm spectrum with the sensitivity of the SPIRE FTS should also provide important information on shock-heated dust for a wide range of outflows. So far, the far-infrared/submillimetre continuum emission from shock-heated dust associated with a bipolar outflow has been clearly detected in only one source, L1551 (e.g., Ladd *et al.*, 1995).

1.5 Main sequence and evolved stars

1.5.1 Mass loss from evolved stars

The high sensitivity of SPIRE to extremely cool dust emission makes it the ideal instrument to map and characterise the very extended material that is expected to surround most evolved stars. Almost all stars with initial main sequence masses below 5-8 $M_{\odot}$ are believed to end their evolution as white dwarfs (Iben & Renzini, 1983), whose maximum (Chandrasekhar) mass is 1.4 $M_{\odot}$ and whose mean mass has been estimated to be only 0.6 $M_{\odot}$. The implication is that large amounts of mass are lost prior to the white dwarf stage, and yet planetary nebula envelope masses (the result of a super-wind at the tip of the Asymptotic Giant Branch, or AGB) are typically found to be only 0.2-0.5 $M_{\odot}$ (e.g., Barlow, 1991). There is thus a “missing mass” problem. Most of the missing mass appears to have been lost before the AGB super-wind phase, during the earlier phases of the first and second ascents of the red giant branch. Our understanding of stellar evolution, and thus of the enrichment of galaxies in heavy elements and dust, will be very incomplete until these earlier mass loss phases are characterised and understood.

It can be extremely difficult to detect the dominant gaseous component of the material ejected by evolving stars - it is only during the brief planetary nebula phase, when the most recently ejected gas becomes ionised, that this component can be easily studied. By contrast, the dust component of the ejected material reveals itself at any phase of evolution via its thermal continuum emission. The IRAS mission discovered many examples of high-luminosity intermediate spectral type objects evolving between the AGB and planetary nebula phases, which were revealed by their warm dust emission at mid- and far-infrared wavelengths. However, the IRAS survey had neither the sensitivity, nor long enough wavelength coverage, to detect the cooler extended dust emission that should be associated with prior AGB phases or with lower-luminosity pre-AGB phases.

The extended ejecta resulting from mass loss will contain cool dust particles heated by the diffuse interstellar UV radiation field to temperatures of 20-40 K, whose emission would peak between 120 and 250 μm if they radiated as blackbodies, and at shorter wavelengths for more realistic $\beta = 1$ or 2 grain emissivity laws. Thus the wavelength domain longward of 200 μm that is covered by SPIRE should sample the declining Rayleigh-Jeans portion of the dust energy distribution which, as demonstrated by Hildebrand (1983), is the best spectral region for determining total dust masses. For 30-K grains embedded in a modest mass loss flow of 10^{-6} $M_{\odot}$ yr.$^{-1}$, with the “standard” dust-to-gas mass ratio and dust grain parameters tabulated by Hildebrand (1983), SPIRE in mapping mode at 250 μm should see a flux per beam in 1 hour that will be well above the predicted instrumental noise and sky background confusion limits. Steady outflows should appear limb-brightened, while the commonly encountered phenomenon of mass loss occurring as a series of bursts and subsequent declines should manifest itself even more easily as multiple discrete shells in the images. By mapping the environs of a range of stars at different evolutionary stages, one should be able to build up a picture of the mass loss history of stars of different masses at different evolutionary stages of their lives. Targets will be selected to be preferentially out of the galactic disc in order to avoid confusion from the galactic plane interstellar medium. There are a relatively large number of such targets available. They will include first-ascent red giant stars and white dwarfs, as well as objects at all evolutionary stages between these two points, e.g. pulsating and non-pulsating AGB stars, including Miras and Carbon stars, post-AGB objects and planetary nebulae, together with the enigmatic R CrB and RV Tau stars. It is expected that multiple shells may be observed around second ascent red giant stars, due to the helium shell flashes that occur as they climb the AGB in luminosity. It is possible that the helium core flash that ends the first ascent of the red giant branch may also have led to the ejection of a significant amount of material from a star. Due to the extreme brevity of this event, the probability of catching a star during the helium core flash is very small, but any material ejected as a result can be detected by SPIRE over much longer timescales.

In addition to mapping the dust emission as described above, the FTS spectrometer mode of SPIRE could then be used to attempt to detect line emission from the CI 370- μm and 609-μm transitions, whose flux ratio is a sensitive measure of the thermal properties of the gas. These lines are two of the dominant cooling lines at the temperatures and densities that are expected to characterise such shells and ejecta. From observations of bright post-AGB object and planetary nebula shells, the CI/CO line ratios appear significantly enhanced relative to those found in the interstellar medium (Keene *et al.*, 1993; Young, 1997; Young *et al.*, 1997), so observations of these lines would be a valuable adjunct to the dust continuum measurements. The overall programme therefore has the potential to greatly increase our knowledge of the properties of the material lost by stars after the main sequence.

1.5.2 Dust discs around main sequence stars

SPIRE will follow up SIRTF observations of Vega-like dust disks, as its high sensitivity and longer wavelength capabilities will make it possible to determine dust masses and emissivities. Fig. 1.9 shows a recently obtained SCUBA JCMT 850-μm image of α PsA (Fomalhaut), illustrating the complex mm-wave extended structure that can be present around such stars. Dust disc energy distributions peak between 60 and 100 μm (Aumann, 1985), so that SPIRE will sample the Rayleigh-Jeans region of the spectrum that is optimal for total mass determinations. For more distant main sequence and post T Tauri stars, it will be able to detect many more systems than is possible with the most sensitive ground-based instruments, such as SCUBA.. For closer systems, SPIRE photometric observations will be able to map the spatial extent of the discs out to much lower surface brightness levels than hitherto possible.

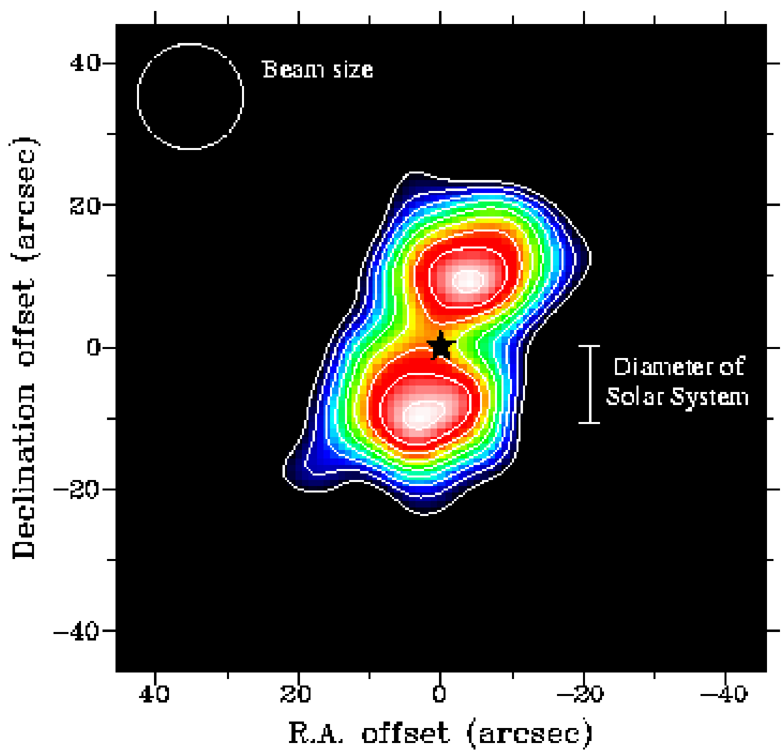

Figure 1.9: 850-μm image of α PsA (Formalhaut) made with the SCUBA bolometer array receiver on the James Clerk Maxwell Telescope (courtesy of Dr. Wayne Holland, JAC)

As a result of SPIRE's sensitivity to very low surface brightness levels, it may be possible to determine whether Vega-like discs have relatively abrupt outer edges, determined perhaps by dynamical shepherding effects, or instead decrease gradually in their surface brightness levels with increasing distance.

1.6 The interstellar medium

The 3.5-m FIRST telescope and the 200 to 650 μm wavelength range covered by SPIRE will, for the first time, enable astronomers to study at high spatial resolution (18-50") the physical and chemical conditions prevailing in the cold phases of the interstellar medium. These observations are essential to understand the changes which occur in the interstellar gas prior to star formation. The mapping and spectroscopic capabilities and the sensitivity of SPIRE will allow these changes to be followed at different scales by observing a variety of galactic sources from diffuse atomic clouds to quiescent molecular clouds. Three key problems of the interstellar medium studies can be addressed with SPIRE: (i) the changes of the dust properties from the warm atomic medium to the dense cold parts of star-forming regions; (ii) the distribution of key molecular species in molecular clouds, including water vapour and its isotopes; and (iii) the cooling of the cold interstellar clouds. None of the above problems will be covered by planned submillimetre projects (LSA/MMA) from the ground or from airborne platforms (SOFIA). In particular, the observations of extended low surface brightness regions and the complete coverage in wavelength from 200 to 650 μm are essential to obtain a detailed view of the cold gas and dust in the interstellar medium from the diffuse to the dense regions. This study of the ISM in our own galaxy will also be immensely valuable to other FIRST (and PLANCK) observations. A thorough knowledge of the characteristics of the far-infrared and submillimetre emission in the Galaxy is a prerequisite to fully exploit the observations of nearby and high-z galaxies; and an understanding of the spatial and spectral properties of the foreground interstellar dust at wavelengths > 200 μm is also important for the study of the cosmic background radiation.

1.6.1 Temperature structure and cycling of dust in the ISM

The average spectrum of the atomic medium at high latitude is well explained by a single temperature at 17.5 K with a ν^2 emissivity law (Boulanger *et al.*, 1996; Dwek *et al.*, 1997). In the galactic plane and nearby molecular clouds, the far-infrared/submillimetre emission as measured by COBE cannot be described by a single temperature and emissivity law and an additional component with lower temperatures is required. Low dust temperatures (15-12 K) have been found in nearby dense molecular clouds based on ISOPHOT far-infrared colours (Laureijs *et al.*, 1996) and studies of nearby molecular clouds using COBE FIRAS and DIRBE data (Lagache *et al.*, 1998). Recently, previously unknown isolated clouds characterised by dust temperatures of about 12 K have been detected in a number of star-forming regions and in one high-latitude cloud by the PRONAOS balloon experiment SPM-PRONAOS (Ristorcelli *et al.*, 1998). These cold temperatures might be related to an increase of dust emissivities in these clouds due, for instance, to grain growth. Cold cores are also seen in extinction at mid-infrared wavelengths with ISOCAM (in Ophiucus) with typical scales of 10 to 30 arcsec. (Abergel *et al.*, 1996). Figure 1.10 shows ISOCAM and PRONAOS maps of the ρ-Oph cloud, showing the need for submillimetre continuum observations to reveal the dominant thermal emission from cold cores.

The transition of the warm diffuse to the cold dense gas occurs at scales significantly smaller than the IRAS, ISOPHOT, PRONAOS and FIRAS beams. The three photometric bands of SPIRE will enable one to characterise the dust temperature from the warm (20-30 K) to the coldest clouds (12 K or less). The angular resolution and the sensitivity of SPIRE will represent an improvement over previous IRAS and ISOPHOT measurements, which would be comparable to the improvement of the ISOCAM results over those of IRAS at 12 μm, and will allow mapping of the distribution of the clouds out to regions of very low-surface brightness. Low-resolution ($\lambda/\Delta\lambda$ = 20 - 30) FTS imaging will allow detailed studies of the changes of the dust properties from the warm periphery of the cloud to its densest parts. The FTS spectral range from 200 to 650 μm is also essential in order to identify the molecular lines which may contaminate the broad-band measurements and to constrain unambiguously both the temperature and the emissivity the dust.

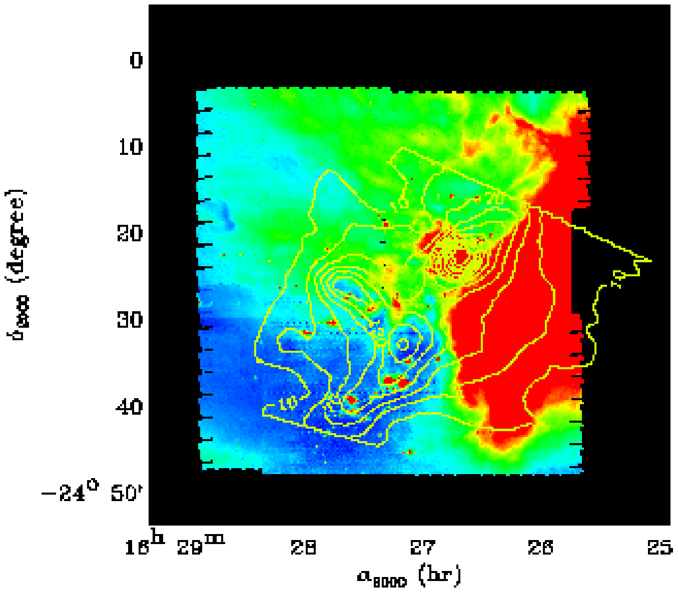

Figure 1.10: The ρ Oph main cloud emission (shown in colour) mapped at 5-8.5 μm with ISOCAM (from Abergel *et al.*, 1996) compared with the emission between 540 and 1100 μm as measured with PRONAOS (shown as contours with steps of 30 MJy/Sr.). The mid-infrared absorption features revealed by ISOCAM coincide with the cold condensations (12-K) detected with PRONAOS.

1.6.2 Spectral imaging with the SPIRE FTS

The FTS spectral resolution is adequate to detect the main atomic and molecular lines expected in SPIRE wavelength range. Bennett *et al.* (1994) have reported the first unbiased spectral survey of the very large-scale far-infrared and submillimetre emission from the Galaxy based on FIRAS results with a 7° beam. The emission is dominated by the dust continuum and the fine structure transition of C^+ at 158 μm which is the major coolant of the neutral gas in the Galaxy. Two transitions of N^+ (at 122 and 205 μm) trace the low-density extended ionised component of the Galaxy. Neutral regions are traced by the 370 and 609 μm lines of CI and by the series of rotational lines of CO from J = 2-1 to 5-4 (at 520 μm). SPIRE will have three orders of magnitude finer angular resolution than FIRAS, enabling much more detailed study of the distribution of the major cooling lines in a variety of regions from diffuse atomic gas to the dense molecular clouds. Besides the main cooling lines, the FTS will also measure a series of ground transitions of major molecules, including those of water vapour (both in the ortho and para states) and its isotopes, other molecules such as O_2, NH_3, NH, and of the ions H_3O^+, CH^+, and NH^+. With the FTS, all of the transitions in the complete spectral range can be probed at once, together with their distribution over the 2-arcminute field of view. In around one day, the FTS will be able to detect cooling lines a thousand times fainter than the C^+ line in a typical 2 x 2 arcminute galactic region.

Molecules: Spectral imaging with SPIRE will allow for the first time study of the distribution and the excitation of a number of key molecular species. The sensitivity of the FTS will ensure the simultaneous detection of the most abundant species and all their transitions in the SPIRE range (see Table 1.2). Amongst these, two important species can only be studied from space. The first is water vapour and its isotopes. ISO results show the important role of water vapour in the interstellar medium, revealing it as one of the most important cooling agent in dense molecular clouds (Cernicharo, 1997; Cernicharo *et al.*, 1997a). Mapping the lowest lying transitions of H_2O and its isotopes will be one of the unique and most important capabilities of FIRST. HIFI will detail the velocity structure of water vapour in the molecular clouds and search for the weaker transitions, and SPIRE will provide an unbiased view of the distribution of the strongest transitions. The second important molecule is CH^+, which probes the densest and warmest zones of PDRs, and whose fundamental rotational transition is at 359 μm. Cernicharo *et al.* (1997c) detected CH^+ with the ISO LWS through the pure rotational transitions from the photo-dissociation region (PDR) of a young planetary nebula, and made the first derivation of the rotational temperature of CH^+. Mapping the J = 1-0 transition of both CH^+ and $^{13}CH^+$ in standard PDRs and in less dense regions will reveal the distribution of this molecule, its abundance, and perhaps help us to understand how it is formed.

Species	λ (um)	ν GHz)	E_{low} (cm^{-1}) *	Transition	Comments
N^+	205	1461	0.0	3P 1 - 0	
OD	216	1391	0.0	3 2 x x - 2 2 x x	12 lines
SH	217	1383	0.0	2 x 0 3 x - 1 x 0 2 x	6 lines
H_2D^+	219	1370	0.0	1 0 1 0 - 0 0 0 0	
HF	243	1232	0.0	1 - 0	
H_2O	269	1113	0.0	1 1 1 - 0 0 0	para
$H_2{}^{17}O$	271	1107	0.0	1 1 1 - 0 0 0	
$H_2{}^{18}O$	272	1102	0.0	1 1 1 0 - 0 0 0 0	
NO	285	1053	5.0	5 1 x 4 - 2 1 x 3	2 lines
NH^+	300	999	0.0		
H_3O^+	301	985	5.2		
NH	317	946	0.0	1 0 1 x - 0 1 x x	9 + 42 lines
CH2	317	946	47	1 1 1 - 2 0 2	
HDO	336	894	0.0	1 1 1 - 0 0 0	
HCO	351	854	2.9	2 1 2 x x - 1 0 1 x x	9 lines
CH^+	359	835	0.0	1 - 0	
CI	370	809	16	2 - 1	
O_2	387	774	16	5 4 - 3 4	
HCO	390	769	0.0	1 1 1 x x - 0 0 0 1 x	6 lines
NO	399	752	0.01	4 1 x 3 - 1 1 x 2	2 lines
H_2S	407	736	14	2 1 2 - 1 0 1	
O_2	419	715	18	5 4 - 3 3	
CH_3D	430	698	26	3 x - 2 x	3 lines
HCO	435	686	8.7	2 1 1 x x - 2 0 2 x x	12 lines
HCO	437	685	2.9	1 1 0 x x - 1 0 1 x x	10 lines
SiH	478	628	0.0		
HCl	479	626	0.0	1 x - 0 2	3 lines
HCl^{37}	480	625	0.0	1 x - 0 2	3 lines
SiH	480	625	0.0		
KH	494	606	20	3 0 - 2 0	
NO	498	602	5.0	4 1 x x - 2 1 x x	6 lines
CO^+	509	590	39	5 5 - 4 4	2 lines
NaH	517	579	9.7	2 0 - 1 0	
CO	520	576	38	5 - 4	
NH_3	524	572	0.40	1 0 0 - 0 0 1	
$^{15}NH_3$	524	572	0.40	1 0 0 - 0 0 1	
CN	529	566	38	5 0 x x - 4 0 x x	21 lines
$C^{17}O$	534	562	38	5 - 4	
H_2O	538	557	24	1 1 0 - 1 0 1	ortho
^{13}CO	544	551	37	5 - 4	
$C^{18}O$	546	549	37	5 - 4	
HNC	551	544	45	6 - 5	
HCO^+	560	535	45	6 0 0 - 5 0 0	
CH	561	535	0.0	1 x 2 x - 1 1 1 x	6 lines
HCN	564	532	44	6 - 5	
SH^+	570	526	0.0		
HCO	584	513	8.7	1 1 1 2 x - 2 0 2 3 x	2 lines
HDO	589	509	16	1 1 0 - 1 0 1	
CaH	592	506	8.4	2 2 x - 1 1 x	3 + 8 lines
HCO	594	504	8.7	1 1 1 1 x - 2 0 2 2 x	2 lines
CI	609	492	0.0	1 - 0	
O_2	614	487	2.1	3 3 - 1 2	

Table 1.2: Lowest transitions of most abundant species in the ISM detectable in the SPIRE range (* 1 K ≡ 0.7 cm^{-1})

Cooling of the atomic gas: The SPIRE FTS range contains the ground state transition of N^+ at 205 μm and the neutral carbon CI transitions at 370 and 609 μm. Together with the spectral imaging capabilities of PHOC below 200 μm, and the high spectral resolution of HIFI, it will be possible for the first time to study the relative importance of the major cooling lines (C^+, N^+, CI and OI) of the atomic gas from the low-density extended ionised regions to the neutral parts of the dense molecular clouds. Measurements of the distribution of the N^+ 205 μm line towards HII region and molecular clouds will give a detailed view of the extent and structure of the ionised gas in a wide density range, 10^2 - 10^5 cm^{-3}, unhindered by extinction. This will help to disentangle the contribution of the warm interstellar medium from extended low-density HII regions in the large scale N^+ emission detected by COBE. CI is a key tracer of interstellar gas with moderate column densities (a few x 10^{21} cm^{-2}) corresponding to intermediate regions between the C^+ and CO layers. CI emission is n the Galaxy as shown by FIRAS. Although ground-based observations will be available in one or both of the CI transitions, it is unlikely that low-surface brightness regions can be mapped from the ground. The ability to measure and map both transitions at once will help to characterise the physical conditions of the transition regions between atomic and molecular clouds. The ratio of these lines is a sensitive tracer of the thermal pressure of the neutral gas for pressures greater than 10^4 K cm^{-3} (Jenkins & Shaya, 1979). For 80 K gas, the 370:609 μm ratio changes from 1 to 5 as the pressure varies from 10^4 to a few x 10^6 K cm^{-3}.

1.7 The solar system

The FIR and submillimetre range is of particular interest for planetary and cometary studies. It is largely unexplored and contains many strong rotational lines including those of a number of very important species which do not have lines in the millimetre range (e.g., halides) or those which have transitions that are not observable from the ground, such as H_2O and O_2. For continuum studies, the FIR range is the region of maximum flux of cold objects such as distant planets or small bodies.

In dense planetary atmospheres, depending on the vertical profile of the absorber, molecular lines appear either as broad (0.1 cm^{-1} to several cm^{-1}), often shallow, absorption features formed in the troposphere, or as narrower (0.001-0.01 cm^{-1}) emission lines formed in the stratosphere. In many cases, especially when species are well-mixed, the line profiles simultaneously exhibit absorption and emission. Heterodyne observations are well suited to narrow features, and broad features can uniquely be observed with an instrument offering a large bandwidth and a moderate (50-400) spectral resolution. The broad width of the features is a serious handicap for airborne observations because the telluric transmission is often significantly variable over the line profile. These considerations make the operation of a space-borne instrument like SPIRE very relevant for planetary studies.

1.7.1 Spectroscopic observations with SPIRE

The giant planets: SPIRE's FTS will explore the full 200-670-μm spectrum of the four giant planets. The main goal will be the search for new minor species, particularly halides (HF, HCl, etc.) and hydrures (e.g., H_2Se) in Jupiter and Saturn, and phosphine (PH_3) in Uranus and Neptune. These so-called disequilibrium species are thermodynamically stable only at deep hot levels but brought to observable levels by upward convection. Their measurement thus provides insight into the importance of vertical transport. A possible difference in the phosphine abundance between Uranus and Neptune could be related to the fact that as Uranus lacks a significant internal heat source, vertical convection is expected to be much more gentle there. A second goal will be the determination of the vertical profiles of the known species (PH_3 and NH_3 on Jupiter and Saturn, as a follow-up of ISO results), thereby characterising other physical processes like photochemistry and condensation.

Models (e.g., Bézard *et al.*, 1986), show that the long-wavelength part of the submillimetre spectrum (200 μm - 1 mm) is richer in lines than the short-wavelength part (100 - 200 μm), making SPIRE very well suited for this study. In particular, it will be able to search for PH_3 in Uranus and Neptune through its multiplets at 374 and 562 μm. This will be a major objective, as the submillimetre range is the only domain where a detection of this species in Uranus and Neptune can be anticipated.

Mars: The first exploration of the 200-670 μm part of the martian spectrum will allow one to derive the vertical profile of water vapour and oxygen and possibly to detect other compounds expected on the basis of photochemical models, such as the long-sought hydrogen peroxide (H_2O_2). Deuterium will also be measured through the HDO lines at 302 and 336 μm. The H_2O profile can be measured at least for two different martian seasons and the $CO:O_2$ and perhaps $H_2O:O_3$ ratios can be determined at least twice over a 4-year period. Such very valuable information will be obtained in concert with HIFI in support of the space missions to Mars.

Comets: Observations of the H_2O lines at 538, 304 and 273 μm, and possibly 399 μm, will allow measurement and monitoring of the water production rates in comets. The minimum detectable production rates will be of a few times 10^{27} s^{-1}. Several comets with $q(H_2O) = 10^{27}$ s^{-1} are visible each year; a systematic study of moderately active comets will thus be possible. SPIRE observations will be complementary with those of HIFI, which will primarily observe the strongest H_2O line at 557 GHz (538 μm). Although HIFI will be more sensitive because of the narrow line widths, SPIRE will observe several lines simultaneously, allowing study of coma temperature and excitation conditions. Also, observations of the higher-frequency lines will be important when the 557 GHz line is saturated, as will be the case for bright comets. In addition, while the 557 GHz line is an ortho transition, other H_2O lines observable by SPIRE are due to para transitions. By combining SPIRE and HIFI data, it will be possible to infer the ortho:para ratio in comets, providing a test of formation conditions. More information on formation conditions will come from the measurement of D/H, which will be determined from HDO at 336 μm and perhaps 302 μm. Should any bright non-periodic comets appear during the course of the FIRST mission, SPIRE will perform a serendipitous search for other species, notably halides, H_2O isotopes, water ions, and radicals, with the FTS having the unique advantage of simultaneous broad-band coverage.

1.7.2 Photometric/spectrophotometric observations with SPIRE

The sensitivity of SPIRE will allow photometric/spectrophotometric observations of faint Solar System objects such as asteroids, icy satellites of Jupiter and Saturn, Centaurs, cometary nuclei, cometary dust, Pluto, and of some Kuiper-Belt objects. Such studies will also be performed by PHOC, and with a somewhat higher sensitivity than SPIRE since the thermal flux of these objects generally peaks at 100 μm or beyond. Nonetheless, the complementarity between SPIRE and PHOC is necessary to investigate spectral variations of emissivity over a wide wavelength range. These observations will provide valuable information on their surface properties (temperature and emissivity). Studies of cometary dust have been carried out using earth-based submillimetre observations but with limited success due to the restricted spectral coverage. In photometric mode, Pluto will be detected by SPIRE to high S/N (~ 100 in 1 hr). Asteroids out to 2.7 AU with D > 10 km, and cometary nuclei with D > 20 km out to 5 AU, will be detected with S/N > 3 in around 1 hr per object. Chiron can be detected at all heliocentric distances (8.5-19 AU) and Pholus at distances out to 15 AU. Only the largest Kuiper Belt objects will be detected (D > 300 km at 40 AU). For the brightest of these objects (Pluto, cometary dust, icy satellites), low-resolution ($\lambda/\Delta\lambda$ ~ 20) FTS spectroscopy will be particularly useful in characterising the icy or mineral composition or the surfaces. This is illustrated by recent ISO/LWS observations showing broad emissions near 45 and 70 μm in the spectrum of comet Hale-Bopp. Similar information will be obtained on the emissivity and compositional properties of the mineral-covered surface of Mars.