Extragalactic Science with Herschel-SPIRE

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Abstract. SPIRE, the Spectral and Photometric Imaging Receiver, is one of three instruments to fly on ESA’s Herschel Space Observatory. It contains a three-band imaging photometer operating at 250, 360 and 520 µm, and an imaging Fourier Transform Spectrometer (FTS) covering 200-670 µm. It will be used for many extragalactic science programmes, a number of which will be implemented as Herschel Key Projects. The SPIRE consortium’s Guaranteed Time programme will devote more than 1000 hours to Key Projects covering the high-z universe and local galaxies. It is also expected that substantial amounts of Herschel Open Time will be used for further extragalactic investigations. The high-z part of the SPIRE GT programme will focus on blank-field surveys with a range of depths and areas optimised to sample the luminosity-redshift plane and characterise the bolometric luminosity density of the universe at high z. Fields will be selected that are well covered at other wavelengths to facilitate source identifications and enable detailed studies of the redshifts, spectral energy distributions, and infrared properties of detected galaxies. The local galaxies programme will include a detailed spectral and photometric study of a sample of well resolved nearby galaxies, a survey of more than 300 local galaxies designed to provide a statistical survey of dust in the nearby universe, and a study of the ISM in low-metallicity environments, bridging the gap between the local universe and primordial galaxies.

1. Introduction
The Herschel Space Observatory (Pilbratt, 2004), scheduled for launch in 2008, is the fourth cornerstone mission in ESA’s science programme. Its key science goals are the detection and investigation of galaxies at high redshift, and the study of star formation and the interstellar medium in our own and nearby galaxies. Herschel will carry a 3.5-m diameter telescope, passively cooled to 80
K, and three science instruments: HIFI, PACS and SPIRE. The operational lifetime of the mission will be at least three years, and approximately two thirds of the observing time will be available to the community as Open Time. In this paper we summarise the key design features of the SPIRE instrument, and outline its capabilities for extragalactic astronomy, using examples from the SPIRE Consortiums Guaranteed Time (GT) programme.

2. SPIRE instrument design and capabilities

SPIRE is designed to exploit the particular advantages of Herschel: its large-aperture, cold, (80 K), low-emissivity (a few %) telescope; unrestricted access to the poorly explored 200-700 $\mu$m range; and the large amount of high quality observing time. It contains a three-band imaging photometer and an imaging Fourier Transform Spectrometer (FTS), both of which use feedhorn-coupled bolometer arrays cooled to 0.3 K. The photometer field of view is 4x8 arcmin. Three bolometer arrays are used for broad-band photometry ($\lambda/\Delta\lambda = 3$) in spectral bands centred on approximately 250, 360 and 520 $\mu$m, with diffraction-limited beam widths of approx. 18, 25 and 36" respectively. The same field of view is observed simultaneously in the three bands through the use of two dichroic beam-splitters. Signal modulation can be provided either by SPIRE’s two-axis Beam Steering Mirror (point source photometry or jiggle-mapping) or by scanning the telescope across the sky (scan-mapping). The FTS has a 2.6-arcminute diameter field of view observed simultaneously by two bolometer arrays covering 200-325 $\mu$m and 315-670 $\mu$m. The FTS spectral resolution is adjustable: the maximum resolution for line spectroscopy is 0.04 cm$^{-1}$, for which $\lambda/\Delta\lambda$ varies between 1200 and 300 over the 200 - 670 $\mu$m range; and the minimum resolution, appropriate for continuum spectrophotometry, is 1 cm$^{-1}$ for which $\lambda/\Delta\lambda$ varies from 50 to 15 between 200 and 670 $\mu$m. A detailed description of the instrument and its observing modes is given in Griffin et al. (2006), and the use of a software simulator of the photometer system for the optimisation of extragalactic surveys is described by Waskett et al. (2006).

The expected SPIRE sensitivities are summarised in Tables 1 and 2 (all sensitivity limits correspond to 5 $\sigma$; 1 hr).

| Table 1. Estimated SPIRE photometer sensitivities |
|-----------------------------------------------|
| Band ($\mu$m) | 250 | 360 | 520 |
| Point source | 3.3 | 3.4 | 3.7 mJy |
| 4 x 4 arcmin jiggle map | 12 | 14 | 16 mJy |
| Time to map 1 sq. deg to 3 mJy rms | 1.8 | 2.5 | 3.2 days |

Note that when observing a point source, the photometer produces a sparsely sampled 4x4 arcmin. map around the source, and likewise, the spectrometer provides a sparsely sampled map of a 2.6 arcmin. diameter. A further update of the SPIRE sensitivity model is currently in progress, and will take into account as-measured instrument performance data. Preliminary results of instrument tests to date show that the instrument-level performance is generally as expected,
Table 2. Estimated SPIRE spectrometer sensitivities

| Band (µm) | 200-315 | 315-450 | 450-670 | Units          | Mode    |
|-----------|---------|---------|---------|---------------|---------|
| Point source | 7.7     | 6.9     | 6.9 - 9.6 | W m$^{-2} \times 10^{-17}$ | Line    |
| 2.6 arcmin. map | 23      | 20      | 20 - 29  | W m$^{-2} \times 10^{-17}$ | Line    |
| Point source | 260     | 230     | 230 - 320 | mJy           | Continuum |
| 2.6 arcmin. map | 760     | 680     | 680 - 950 | mJy           | Continuum |

although further tests and confirmation are needed for the spectrometer. However, it should be noted that, as with many cryogenic infrared space instruments, predicted sensitivity figures are subject to large uncertainties (at least a factor of two) due to uncertainties the instrument performance in flight and, in the case of SPIRE, the effective telescope background.

3. Extragalactic capabilities of SPIRE

SPIRE will be used in conjunction with the other Herschel instruments, particularly PACS, to carry out a number of coordinated observational programmes. For the investigation of high-$z$ galaxies, the PACS and SPIRE photometers will together provide a multi-band imager covering the FIR-submm peak in the cosmic infrared background; and they will be able to carry out surveys over much larger areas than have been done from the ground.

For nearby galaxies, ISO was the first satellite capable of doing FIR spectroscopy on nearby galaxies, and demonstrated the value of this in determining the nature, excitation, composition of the interstellar medium and the influence of AGN activity. Herschel, using all three instruments, will extend this to modest redshift and allow vastly more galaxies to be examined with much better angular resolution. It will be capable of multi-band imaging and spectroscopic studies of nearby galaxies to map out the global properties of the ISM and the properties of gas and dust in a variety of galaxy types and environments, and to make detailed investigation of the impact of metallicity on the ISM and the interaction of the ISM with central AGN.

In this section we give some examples of such projects from the SPIRE consortium’s GT programme. All of these observations will be implemented as Herschel Key Projects - programmes that will (i) exploit unique Herschel capabilities to address important scientific issues in a comprehensive manner, (ii) require a large amount of observing time to be used in a uniform and coherent fashion, and (iii) produce well characterised and uniform datasets of high archival value.

3.1. High-redshift galaxies

Approximately 850 hours of SPIRE GT will be devoted to the high-$z$ galaxy programme, and the PACS consortium will use about 650 hrs of their GT on a related and closely coordinated programme. This will be one of the flagship projects for Herschel and will address important scientific issues such as number count models, bolometric (as opposed to single-band) luminosity functions,
formation and evolution of galaxy bulges and ellipticals, structure formation, cluster evolution, the history of energy production, the AGN-starburst connection, and cosmic infrared background fluctuations.

The main science driver for the SPIRE high-z GT programme is to measure the bolometric luminosity density of the Universe as a function of redshift. In order to do this it is essential to measure the SEDs of the individual sources and to carry out a number of surveys of different depths. The programme therefore consists mainly of a set of blank field imaging surveys (to be done in scan-map mode), forming a multi-tiered “wedding cake” covering a range of field sizes, from 0.04 to several tens of square degrees, and depths, from a few mJy to several tens of mJy rms. The smaller fields will be observed to a 5-σ depth comparable to or below the SPIRE extragalactic confusion limit (expected to be in the range 20-30 mJy at 40 beams/source) depending on the wavelength and the adopted source count model (e.g., Vaccari et al. 2006).

The “wedding cake” will be designed to sample the luminosity-redshift plane and characterise the bolometric luminosity density of the universe at high redshift. The wider fields will also sample a range of environments, allowing us to test theories of structure formation. Fields will be selected that are well covered by XMM-Newton, Spitzer, SCUBA-2, PACS-GT and near-IR surveys, to facilitate source identifications and enable detailed studies of the redshifts, spectral energy distributions, and infrared properties of detected galaxies.

Some of the deeper wedding cake fields will be used to carry out a multi-band $P(D)$ analysis on an area of approx. 1 sq. deg. to measure fluctuations down to 3 mJy (about 1 source/beam) and so probe the properties of the number counts below the confusion limit. The availability of multi-band data will provide additional diagnostic capabilities in discrimination between different source population models. The survey will also allow a unique search for FIR background fluctuations originating from sources below the confusion limit and associated with large-scale structure and galaxy clustering. The shallow tiers of the GT survey will be used to investigate clustering on angular scales $< 10$ arcmin. (finer spatial scale than can be probed with Planck). The background fluctuations on this scale are sensitive to the non-linear clustering within a dark matter halo, and the physics underlying the formation of far-infrared galaxies within a halo (Cooray & Sheth, 2002). The large-area and multi-wavelength fields will also enable the properties of ordinary galaxies below the confusion limit to be investigated through stacking analyses.

The GT programme also includes observations of a sample of 15 rich clusters between $z = 0.2$ and 1. Gravitational lensing of background galaxies will allow the detection limit to be extended below the blank field confusion limit to about 5 mJy. In addition, these observations will be sensitive to the Sunyaev Zel’dovich effect, which still produces a significant increment in the CMB in the longest-wavelength channel of SPIRE. The shorter wavelength bands will be used to subtract the contribution from cluster galaxies.

Follow-up spectroscopy of selected sources detected in the GT surveys is expected to be carried out with Herschel and with ground-based facilities (ALMA and 10-m class optical/NIR telescopes). The spectrometers in all three Herschel instruments will give unique access to the most important cooling lines of inter-
stellar gas, which give very important information on the physical processes and energy production mechanisms, and the roles of AGN and star formation.

3.2. Galaxies in the local universe

The SPIRE local galaxies GT programme comprises three Key Projects, requiring approximately 100 hours each: Physical Processes in the ISM of Very Nearby Galaxies, The ISM in Low Metallicity Environments, and The Herschel Galaxy Reference Survey. The first two are joint PACS-SPIRE projects, and the third is SPIRE only.

ISM in Nearby Galaxies: Spatially resolved photometry and spectroscopy with SPIRE and PACS will be carried out on a sample of 15 nearby well-studied galaxies, including examples of early and late type spirals, low mass spirals, edge-on spirals, starburst spirals, starburst galaxies, quiescent dwarfs, starburst dwarfs, Seyferts, and ellipticals. Additional spectroscopic data will be obtained with HIFI. These observations will allow the detailed SEDs and dust properties to be determined, and the variation and evolution of chemistry and metallicity to be studied (both within a galaxy and across the range of galaxy types).

Low Metallicity Dwarf Galaxies: Much progress has been made in characterising galaxies at high redshifts; but the objects discovered so far are already metal-rich, implying that they already have a history of star formation and metal enrichment processes. Although we are not yet able to observe the earlier stage in which primordial galaxies are undergoing their initial episodes of star formation, we do have access to low metallicity dwarf galaxies in the local universe that can serve as analogues to the high-z building blocks from which galaxies are believed to have formed through mergers.

A comprehensive programme of PACS and SPIRE photometry will be implemented to study a sample of 55 dwarf galaxies, covering a broad metallicity range of 1/50 to 1/3 solar. Additionally, 60 to 600 $\mu$m spectroscopy using PACS and HIFI will be obtained on selected sources. The observations will shed light on the influence of metallicity on the UV radiation field, gas and dust properties, and star-forming activity, the effect of the dust properties on the heating and cooling processes in the low-metallicity ISM, and on the impact of the super star clusters prevalent in dwarf galaxies on the surrounding gas and dust.

The Herschel Galaxy Reference Survey: SPIRE will be used to carry out photometry of a sample of 320 local galaxies, constituting a benchmark survey of dust in the local Universe, and providing the first accurate measurements of the amount of dust both inside and outside galaxies. The primary sample (155 galaxies) comprises objects with K(2MASS) < 9 (descendents of early universe luminous objects) and with distances between 15 and 25 Mpc (allowing the galaxies to be spatially resolved with a single pointing). A secondary sample of sources with K = 9 - 12 will extend the mass range. This survey will also help relate present-day galaxies to their high-z ancestors, and reveal how dust mass and distribution depend on galaxy type, environment, and luminosity. For example, because the sample encompasses all environments from the field to rich clusters, it will enable an investigation of the as-yet unknown process that appears to inhibit star formation in rich environments (Kaufmann et al., 2004).
3.3. Dust properties

Understanding dust properties and their dependence on environment is vital for the correct interpretation of FIR and submm. observations of galaxies (Jones, 2006). One of the SPIRE galactic Key Projects, *The Evolution of Interstellar Dust*, is very relevant in this respect, and will provide important results for the extragalactic programmes. It involves systematic photometric and spectral surveys of the ISM covering the widest possible range of extinction, illumination, density, history, and star forming activity. It will trace the nature and evolution of dust in relation to the physical, dynamical and chemical properties of the ISM in different environments: diffuse shock processed dust, cirrus, molecular clouds, low excitation PDRs, hot PDRs with HII regions, pre-stellar cores, and protostars. The results will allow study of the various processes acting on dust particles (fragmentation, coagulation, condensation, evaporation, photo processing) in all ISM environments from the most tenuous to the most dense.

4. Conclusions

SPIRE, in conjunction with the other Herschel instruments, will make major advances in extragalactic astronomy. The Guaranteed Time programmes summarised here (which take up more than half of the SPIRE GT), serve as examples to illustrate the scientific capabilities of the instrument and the mission. It is foreseen that there will be many more extragalactic programmes in Open Time.

Acknowledgments. In addition to the authors of this paper, the SPIRE Extragalactic Science Team includes: Asier Abreu, Rick Arendt, Hervé Aussel, Tom Babbedge, George Bendo, Andrew Blain, Jamie Bock, Alessandro Boselli, Veronique Buat, Jordi Cepa, Pierre Chanial, Sarah Church, Dave Clements, Asantha Cooray, Jon Davies, Fred C. Dobbs, Darren Dowell, Gianfranco De Zotti, Eli Dwek, Simon Dye, Steve Eales, David Elbaz, Erica Ellingson, Mark Frost, Frederic Galliano, Ken Ganga, Bruno Guiderdoni, Mark Halpern, Evanthia Hatziminaoglou, George Helou, Kate Isaak, Rob Ivison, Guilaine Lagache, Glenn Laurent, Bruno Maffei, Phil Maloney, Hien Nguyen, Alain Omont, Pasquale Panuzzo, Marc Sauvage, Richard Savage, Bernhard Schulz, Douglas Scott, Luigi Spinoglio, Jason Stevens, Mattia Vaccari, Ian Waddington, Tim Waskett, Christine Wilson, Kevin Xu.

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