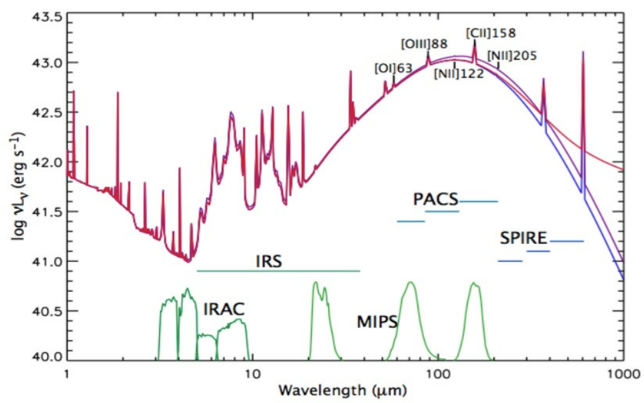
Science

Introduction

The study of galactic evolution has matured enormously over the past 15 years, producing a paradigm which integrates the theory of galaxy formation and evolution with the larger theory of cosmology and structure formation. However, while the broad outlines of galaxy evolution have taken shape, the details have yet to be filled in. Our understanding of the exact physical processes that drive the growth of galaxies — most notably star formation and its interaction with the ISM — are acutely limited.

Observations of star formation and the ISM in nearby galaxies form a vital bridge between in-depth studies of individual interstellar clouds and star-forming regions in our Galaxy and the globally integrated measurements of distant galaxies. To understand galaxies we must first understand the physical processes that regulate their evolution: the cooling and phase transitions in the gas, the formation of stars, and the return of radiant and mechanical energy from those stars into the interstellar medium. A better understanding of these processes is a *sine qua non* for solving the larger problems of star formation and galaxy formation overall.

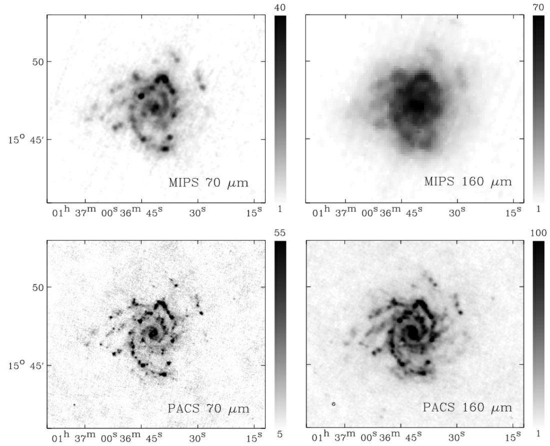


I - Linking Star Formation to the Interstellar Medium in Galaxies

Approximately half of the bolometric luminosity of the Universe is channeled through the far-infrared (FIR). This emission carries information on the stellar populations that heat the dust, as well as on the structure and physical conditions of the absorbing dust itself. Dissecting this information in practice is hampered by the highly clumped and variable distributions of the stars and dust, and the presence of multiple dust components.

IRAS established some basic global trends in infrared (IR) luminosity and spectral energy distribution (SED) shapes as functions of galaxy type and luminosity. The ISO and Spitzer missions brought the next breakthrough, by resolving nearby galaxies for the first time in the mid-IR, and by mapping separately the emission of individual dust grain components, each with its own stellar heating population: (1) warm sources associated with gas and dust clouds (HII regions) surrounding young (<10 Myr old) star-forming regions, especially prominent in the mid-IR continuum; (2) a more diffuse, extended, and cooler dust component heated by stars with a range of ages, which dominates the FIR emission; and (3) mid-IR band emission from large PAH molecules, transiently heated by single UV and optical photons in PDR regions surrounding young star clusters and by the general interstellar radiation field (Draine et al. 2007, ApJ, 663, 866). These Spitzer and ISO observations have been especially successful in establishing the physical connections between the heating of the mid-IR emitting dust and young stars, but they cannot separate longer-wavelength FIR-emitting components of most galaxies, where the bulk (~90%) of the dust emission occurs, because of insufficient angular resolution.

Herschel/PACS will make the next breakthrough in this problem, by mapping galaxies with unprecedented spatial resolution (~6'' - 10''), precisely over the 70-170 micron wavelength range where the dust emission peaks (Figure 1). This angular resolution projects to linear scales of 30-40 pc (M33) to 300-500 pc at the median 10 Mpc of the KINGFISH galaxies. This is a key astrophysical enabler of Herschel, allowing us for the first time to resolve the peak dust emission of individual star-forming complexes in these galaxies, and cleanly separate the relatively warm dust surrounding young stars and galactic nuclei from the cooler and more extended diffuse emission. Combining these PACS images with the longer-wavelength SPIRE maps and the shorter Spitzer, GALEX, and groundbased observations from SINGS will produce a powerful set of high-resolution bolometric and pixel-resolved SED maps extending from the UV to the FIR. These will reduce the uncertainties in the IR and multiwavelength SFR indicators by a factor >2, reduce uncertainties in the the dust masses of galaxies by factors ~3-5, and address a wide range of science questions as described below. The regions targeted for PACS line imaging, when combined with Spitzer/IRS spectra, will provide additional information on the physical conditions and density structures of the ISM, on scales much smaller than the beam size.



NGC 628 observed at 70 and 160 µm by Spitzer/MIPS (as part of the SINGS project)

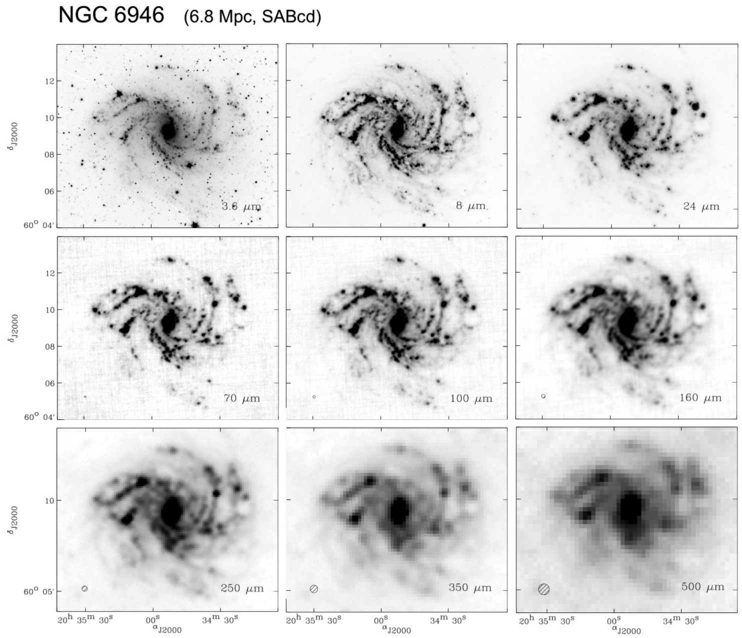
and Herschel/PACS.

I.a - Understanding and Modeling Dust Heating and Emission in Galaxies

The detailed FIR SED maps from PACS+SPIRE will break many of the degeneracies that plague the interpretation of current observations of dust in nearby galaxies. The dust emission and temperature distribution is determined by several factors including the local radiation field intensity, dust opacity, grain size distribution, and composition. ISO and Spitzer advanced further by providing measurements to treat successfully the heating of the PAH grains and larger FIR-emitting grains separately. However, the Spitzer wavelength coverage (<=160 micron) did not include the full dust SED peak, and hence cannot deliver reliable dust temperatures, masses, or emissivities. With the extended wavelength coverage of the PACS+SPIRE FIR maps, the SINGS SEDs at shorter wavelengths, and the suite of dust models developed by Draine & Li (2007, ApJ, 657, 810), we can constrain dust emission from a wide range of temperatures, (from hot, at T ~100 K, to cool, at T~10 K). Only then can we test for changes in the wavelength-dependent emissivities of the dust with metallicity, molecular/atomic gas fractions, and local radiation field environments. The same data will constrain the composition and abundance of the grains, over a much wider range of ISM environments than can be probed in the Galaxy alone.

The high spatial resolution will also reveal the roles of different age stellar populations in heating the FIR emitting dust. These populations have very distinct spatial distributions (readily traced by our UV, broadband visible, and H-alpha imaging), and by correlating these with the corresponding distributions of IR surface brightness over a wide baseline in wavelengths we can identify the dominant heating populations. The diversity of stellar populations, types, surface brightnesses, SFRs, and local ISM conditions in the KINGFISH sample is critical for separating the effects of different radiation field environments and of dust properties on the IR emission.

The high angular resolution Herschel data will also break the impasse on interpretating the origins of the mid-IR PAH band emission at 3-18 micron. Recent results from Spitzer suggest that the global PAH emission of galaxies is produced by a combination of PDRs surrounding star-forming regions and diffuse dust heated by the general interstellar radiation field, with the relative proportions varying significantly within and between galaxies (Helou et al. 2004, ApJS, 154, 253). However other recent studies have suggested tight correlations of the PAH emission with the star formation component (e.g. Roussel et al. 2001, A&A, 372, 427, Forster Schreiber et al. 2004, A&A, 419, 501) or the cold dust component (Haas et al. 2002, A&A, 385, L23) taken alone. Much of this divergence has been driven by the limited angular resolution and/or sensitivity of extant maps of the diffuse interstellar dust component. Herschel/PACS for the first time will map the peak cool dust emission with sufficient resolution to compare directly to the structure of the Spitzer 8 micron band PAH emission, and thus probe directly any links between the heating of the two dust components.



NGC 6946 observed from 3.6 to 500 μm with Spitzer/IRAC and MIPS and Herschel/PACS and SPIRE.

I.b - Robust Multi-Wavelength Star Formation Rates and the Schmidt Law

The detection of large populations of dusty star-forming galaxies at high redshift by ISO and Spitzer has underscored the need for reliable calibrations of IR-based and UV/optical+IR-based SFR diagnostics, and a physical understanding of the basis and limitations of these tools. The SINGS project has confirmed the close association of the warm 24 micron dust component with the youngest star-forming population in HII regions (Calzetti et al. 2007, ApJ, 666, 870), which led to the development of reliable, extinction-corrected SFR indicators (Calzetti et al. 2007, Kennicutt et al. 2009, ApJ, in press). However the physical basis and applicability of such calibrations to high-redshift galaxies (with vastly different physical properties) is unclear, because the 24 micron emission comprises only ~10% of the total dust emission, and thus the IR `bolometric corrrections' are huge. The sub-kpc resolution maps from Herschel PACS will directly trace the relation between the FIR emission in the 70-170 micron range and the local star formation, to: (1) calibrate directly SFR diagnostics based on UV+IR luminosity and Halpha+IR luminosity; (2) calibrate and test the limitations of SFRs based in IR measurements alone, bearing in mind future applications to the distant universe from ALMA; (3) fit the observed correlations with spatially-resolved SED maps and dust models (e.g., Draine & Li 2007), to predict the reliability of these methods in environments that differ substantially from those found in local galaxies.

The extinction-corrected KINGFISH SFR maps will span a wider range of SFR/area than currently available; in particular the UV+IR diagnostics will probe low surface brightness regimes where H-alpha no longer provides a statistically reliable local SFR measure. These data, when combined with our extensive suite of high-resolution HI and CO maps, will allow us to investigate the spatially-resolved correlation between the SFR surface density and gas surface density (the Schmidt Law; Kennicutt 1998, ApJ, 498, 541; Kennicutt et al. 2007), variations in this relation within discs (e.g., spiral arms, interarm regions, bars, circumnuclear regions), and the physical nature of the star formation thresholds at low SFR densities (e.g., Martin & Kennicutt 2001, ApJ, 555, 301).

I.c - The Radio-IR Correlation

Radio continuum emission is widely used as a tracer of recent star formation for galaxies both at low and high redshift. There is a tight empirical correlation between the centimetre emission (> 1 GHz, mostly due to synchrotron emission from cosmic ray electrons) and the FIR luminosity (e.g. Condon 1992, ARAA, 30, 575). Although the relation must be rooted in common dependencies on star formation, it is unclear how presumably unrelated physical processes affecting the propagation of CR electrons and the heating of dust grains work together to yield a nearly ubiquitous correlation over many orders of magnitude. Spitzer revealed local correlations in the spatial distributions of 70 micron and non-thermal radio emission that reflect an `age effect'; the CR electron populations of galaxies with intense star formation largely arise from recent episodes of enhanced star formation activity and have not had time to diffuse significant distances (Murphy et al. 2006, ApJ, 651, L111). Herschel will advance these investigations by extending observations to much larger ranges of wavelengths, spatial scales, and physical parameters than possible so far. By combining Herschel data with the high quality 20 cm WSRT-SINGS data in hand (Braun et al. 2007, A&A, 461, 455), and, at a later stage, with multiwavelength data from the EVLA, we will be able to study the FIR-radio correlation with a level of detail that will probe the underlying physics of the radio-IR relation on scales down to ~40 pc.

II - The Inventory of Cold Dust and Gas in Galaxies

The full inventory of the dust emission from galaxies has thus far been hindered by the lack of space capabilities beyond 200 micron and by the difficulty in mapping the low surface brightness submillimetre emission of nearby galaxies from the ground. As a result our current observations cannot unambiguously measure and enable us to interpret the emission from colder dust (T<15 K) in galaxies, which may represent a major, perhaps even dominant, fraction of the total dust mass. The abundance of very cold dust is controversial. Tentative detection of extended cold dust has been reported for a handful of nearby spiral, elliptical, and low metallicity dwarf galaxies, based on submillimetre or FIR observations (e.g. Galliano et al. 2003, A&A, 407, 159; Dumke et al. 2004, A&A, 414, 475; Meijerink et al. 2005, A&A, 430, 427; Hinz et al. 2006, ApJ, 651, 874). However, a recent analysis of SINGS+SCUBA data by Draine et al. (2007) concludes that very cold (T<10K) dust could contribute no more than 50% of the total dust mass. These uncertainties arise directly from the difficulty in inferring cold dust temperatures and masses from extrapolated FIR observations. Herschel will directly resolve this issue by mapping nearby galaxies to ~500 micron. Combining these data with our ongoing groundbased imaging at 850 micron and 1100 micron imaging with LABOCA, MAMBO-2, and, soon, SCUBA-2 will enable us to map the distribution and temperature of the cooler dust, especially in low surface brightness regions which are difficult for ground-based submillimeter telescopes, and to constrain the cold dust masses of the galaxies to within a factor 1.5.

III - The Energy Balance of the star-forming ISM

The spectral coverage of the PACS instrument includes several of the most important cooling lines in the atomic and ionized ISM, most notably [CII]157.7 μm, [OI]63.2 μm, [OIII]88.4 μm, [NII]121.9 μm and 205 μm (and all outside the wavelength range of the Spitzer IRS spectrometer). Even with this limited set of lines the range of astrophysical applications is broad, including mapping of the cooling rates and derived UV radiation intensities in active star-forming regions and the more quiescent ISM, testing and calibrating fine-structure lines such as [CII] 158 μm as a star-formation diagnostic, and constraining the metal abundance scale in HII regions.

III.a - Cooling of the Interstellar Medium

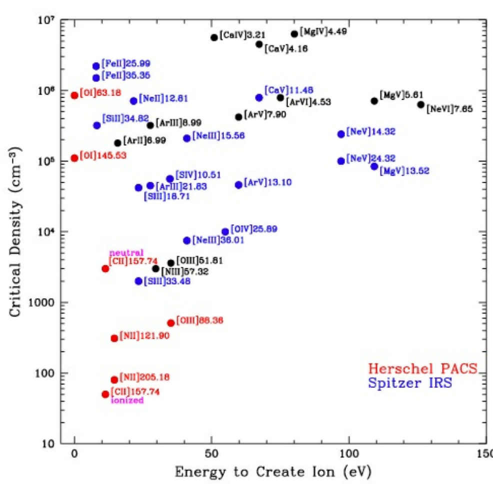
The [CII]158 and [OI]63 lines dominate the cooling of the warm neutral medium in normal galaxies. Photoelectrons liberated from dust grains by UV photons provide the heat input for the gas (e.g., Hollenbach & Tielens 1999, Rev Mod Phys, 71, 173). The heating is relatively inefficient (0.1 - 1%), with the efficiency determined mainly by the ratio of UV radiation field to gas density (G_0/n). Observations of the FIR cooling lines in representative samples of local star-forming galaxies were pioneered with ISO (e.g., Malhotra et al. 1997, ApJ, 491, L27; 2001, ApJ, 561, 766; Contursi et al. 2002, AJ, 124, 751). These studies clearly showed that (1) while the [CII]158 emission dominates the line cooling, the ratio of [CII]/FIR decreases by more than an order of magnitude (from 0.004 to less than 0.0004) for galaxies with high luminosity and/or warm dust temperatures, (2) the [OI]63/[CII]158 flux ratio ranges from 0.2 - 2, with [OI] taking over as the primary coolant for the high luminosity, warm sources, and (3) the [CII]/PAH ratios show no such trends with dust temperature or luminosity. These results are broadly consistent with a model that explains the ISM as having a diffuse or cirrus-like component, where [CII] often dominates the cooling and the smallest grains provide the bulk of the heating, and having an ``active'' component, where [OI]63 is stronger than [CII]158. The mechanism responsible for heating these ``active'' regions is uncertain, but shock heating is one candidate, and energy injection from deeply embedded star formation in dense regions is another. Unfortunately the poor spatial resolution of ISO and the small samples of detected sources make direct comparisons to models extremely difficult (e.g., Kaufman et al. 1999, ApJ, 527, 795; Contursi et al. 2002).

Herschel promises to revolutionize the study of the energetics of the neutral ISM in nearby galaxies. The combination of Herschel, Spitzer, and SINGS ancillary data will trace in a comprehensive way the heating and cooling paths for the gas and dust at similar spatial resolutions. The combination of Herschel and Spitzer spectra provides critical measurements of the physical conditions in the ISM -- temperatures, densities and pressures, local UV radiation strength, and hardness -- this ultimately constrains the clumping of the gas on scales much smaller than the Herschel or Spitzer beams. Fitting the observed line fluxes to photodissociation region and shock models (Kaufman et al. 2006, ApJ, 644, 283), will isolate the dominant heating processes in nuclear, arm, and interarm regions. As with the galaxy selection, a statistically robust target sample spanning a wide range of physical properties is critical; our subset of optically-selected and IRAC/MIPSselected spectroscopic targets cover the maximum ranges of metallicity, luminosity, surface brightness, extinction, ionization, H_2/HI fraction, 8 micron/24 micron ratio, and radiation field strengths and shapes avaiable in the parent SINGS sample.

The UV heating efficiency in the ISM is a function of the dust-to-gas ratio, particularly the abundance of the smallest dust grains, which are most efficient at converting UV radiation into thermal photoelectrons. Our Spitzer datasets provide a unique probe of this parameter. In some of our targets the heating may not be dominated by UV radiation, but by shocks driven by cloud collisions or by X-ray sources such as active galactic nuclei (AGNs); these regions will show disproportionately strong cooling. The importance of understanding the ISM heating and cooling balance under a variety of conditions cannot be overstated. This balance is intimately linked with the equilibrium of the different ISM phases, and may dictate the fragmentation of molecular clouds ($M_{Jeans} \sim T^{3/2}$) and ultimately the stellar initial mass function. KINGFISH will be the first programme to study the heating and cooling of the ISM in a very large variety of extragalactic environments.

III.b - The Range of Physical Conditions of the ISM

With the 5-38 micron Spitzer spectra already in hand, these ambitious goals can be addressed by mapping just a few of the key interstellar cooling lines accessible by PACS. For the neutral ISM the [OI]63 and [CII]158 lines (together with the dust continuum, already obtained with PACS/SPIRE imaging) provide the most potent combination. The two lines dominate the gas cooling with very different density dependences ($n_{crit} \sim 8 \times 10^5$ and 3×10^3 cm^{-3} , respectively). Thus the [OI]/[CII] ratio provides a measure of the gas density, while ([OI]+[CII])/LIR provides a measure of the heating efficiency. The [CII] line by itself is insufficient, because it cannot provide a measure of the density and accounts for only part of the gas cooling. With its high critical density [OI] 63 is a superb tracer of warm or hot neutral gas, and will clarify the nature of the unexpectedly strong H2 rotational line emission (exceeding what was expected from PDRs) observed from SINGS star-forming galaxies (Roussel et al. 2007, ApJ, in press). For the ionized gas components the combination of [OIII]88 and [NII]122,205 provide comparable diagnostic leverage, with a resolution of < 300 pc). This resolution is comparable to the sizes of giant star-forming complexes, and the scales over which the formation of molecular clouds is triggered. The [NII] and [OIII] lines were detected in very few galaxies with ISO, yet they provide a direct measure of the ionized gas in the obscured, star forming complexes and allow for an estimate of the gas density, and the effective temperature of the ionizing stars. In particular, the [NII]122/205 micron line flux ratio is a sensitive probe of gas with densities of $10 < n_e < 100$ cm^{-3} , much lower than probed with the mid-IR [SIII] lines seen with the IRS on Spitzer.



Key diagnostic lines for the ISM, in terms of ionization potential and critical density. Red : lines within the spectral coverage of the Herschel PACS spectrometer. Blue : lines within the spectral coverage of the Spitzer IRS instrument.

III.c - [CII] as a SFR Indicator

The role of the [CII]158 line as a primary coolant of the neutral ISM and its high luminosity (readily detectable beyond z = 5 with ALMA) has suggested its use as a quantitative SFR tracer at for high-redshift galaxies, but its reliability needs to be rigorously tested with Herschel. ISO imaging of the spiral arms in M31 has shown that the [CII] emission follows the H-alpha and Spitzer 24 micron emission, suggesting its use as a star formation diagnostic, at least on small scales

(Rodriguez-Fernandez et al. 2006, A&A, 455, 963). However, comparisons of global [CII] and FIR luminosities of galaxies show that this correlation sometimes breaks down (e.g., Malhotra et al. 1997), in the regime where [CII] no longer dominates the cooling, or when starlight from evolved populations dominates the grain photoelectric heating. Our KINGFISH observations will test the strength of the coupling between the [CII]158 line luminosity and the SFR across the full range of abundances, radiation fields, and ISM physical conditions present in normal galaxies today, using the wide suite of SFR diagnostics from the combined Herschel and SINGS data.

III.d - The Metal Abundance Scale

The dominant cooling line for the ionized phase of the ISM is the [OIII]88 line (and its doublet at 52 micron). Combining our Herschel measurements with matched-aperture optical spectra from SINGS and the literature will help resolve the longstanding factor 2-3 discrepancy between different approaches to calibrate the HII region metal abundance scale (auroral lines, oxygen recombination lines, nebular photoionization models, e.g., Perez-Montero & Diaz 2005, MNRAS, 361, 1063). Measurements of the [OIII]88 line, which arise from the ground level of the optical [OIII] 4959,5007 transitions, provides an independent measurement of the OIII abundance that can be used to test for the presence of local temperature fluctuations, which are thought to play a role in producing the discrepant metallicity calibrations. Calibration of the density dependence of the emission is provided by the SINGS spectroscopy of the [SIII]18.7 micron and [SIII]33.5 micron lines, an excellent example of the power of combining Spitzer and Herschel spectroscopy.

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