Physical Processes in Galaxies in the Local Universe:
A Proposal for a JCMT Legacy Survey

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Abstract

We propose a survey with the JCMT using SCUBA-2 and Harp-B of a sample of 331 nearby galaxies. This data set will be unique for studying the physics of the dusty interstellar medium (ISM) in galaxies as well as the interplay between star formation and the ISM. With a large, well-selected sample, we will be able to search for variations in the physical processes in the ISM as a function of galaxy type, metallicity, star formation rate, mass, and environment. By limiting our sample to galaxies closer than 25 Mpc, we will be able to study spatial scales of 0.2-2 kpc and to search for variations inside a single galaxy as well as between galaxies. Specific science goals include: searching for evidence of cold dust and measuring its mass fraction in galaxies of different types; measuring the amount of warm, dense molecular gas associated with star formation using the CO J=3-2 line; comparing galaxies with similar morphologies and luminosities in the field and in the Virgo cluster to determine the effects of cluster membership; using CO rotation curves to trace the dark matter distribution and the frequency of occurrence of nuclear gas concentrations which may feed central starburts or black holes; measuring the local submillimetre luminosity function and dust mass function to luminosities up to 100 times fainter than previous studies.

This survey will produce the first large sample of nearby galaxies observed with good spatial resolution at submillimetre wavelengths, Our proposed sample consists of two parts: 299 galaxies randomly selected from an HI flux-limited sample, plus the 32 remaining galaxies from the SINGS sample that were not selected as part of the random sample. The scientific return from this project will be a solid understanding of properties of dusty ISM in galaxies and how those properties are affected by their environment, both internal (spiral arm, metallicity) and external (galaxy morphology, cluster membership). The images and catalogs that will be produced from this survey will serve as a valuable path-finder for concurrent and future instruments such as Herschel, SOFIA, ALMA, and JWST. **In total, this survey requires 152 hr of grade 1-2 weather and 227 hr of grade 3 or good grade 4 weather**, of which 12 and 47 hr, respectively, are used for the additional SINGS sample.

1 Scientific Justification

1.1 Introduction

Star formation is arguably the single most important process that drives galaxy evolution. Star formation ultimately enriches both the interstellar medium (ISM) and intergalactic medium (IGM) with metals and continually changes the balance between the amount of gaseous material and the number of stars within galaxies. The importance of star formation in the early universe has been amply demonstrated by the discovery of an important population of faint submillimetre galaxies (e.g. Smail et al. 1997). However, only integrated fluxes and spectra can be obtained for galaxies at cosmological distances, while detailed imaging is required for a solid understanding of the physical processes within galaxies. This proposals aims to "bridge the gap" between the local and the distant universe by determining the dust and gas distribution and its relationship to star formation in an unbiased sample of nearby galaxies.

Star formation in galaxies is impacted by both the physical conditions present in the local ISM and by the broader surrounding galactic environment. From detailed studies of the Milky Way, we know that star formation occurs in the densest parts of the ISM, particularly in dusty cores rich in molecules located inside giant molecular clouds (e.g. Lada et al. 1991ab). Although Galactic studies can probe the important details of the star formation process, such as the clump and stellar mass functions (Motte et al. 1998; Kroupa et al. 2002), they are limited in the range of environment to those found within our own Galaxy. To determine the effect of major changes in environment, such as metallicity and galactic structure, on the physical processes and structure of the dense ISM and its associated star formation, we must look to studies of other galaxies in the local universe.

Submillimetre observations are the best tools for probing the cool dusty regions that are the sites of star formation and contain a significant mass fraction of the ISM in galaxies. Continuum observations at 850 and 450 μm probe the majority of the dust mass in a galaxy (Galliano et al. 2003; Regan et al. 2004), while spectral line observations of CO provide a tracer for molecular hydrogen gas (Young & Scoville 1991). The advent of SCUBA-2 and HARP-B on the JCMT provides us with a unique opportunity to carry out a large, statistically well-selected survey of the dust and molecular gas in the nearby universe. We propose to survey a well-chosen sample of 299 galaxies with distances between 2 and 25 Mpc selected on the basis of their HI flux. To this random sample, we have added the 32 SINGS galaxies (Kennicutt et al. 2003) which meet our selection criteria but were not included in the random sample; the rich multi-wavelength database available for these galaxies makes them an important, complementary addition to our sample. With these distance limits, we will be able to probe variations *inside* a single galaxy on spatial scales as small as 0.2-2 kpc, in addition to being able to search for differences in global properties between galaxies. The sample is chosen to be sufficiently large to allow for comparison of galaxy properties as a function of morphological type, luminosity, and cluster membership. The results of this local universe survey will be unique continuum and molecular line data sets in terms of sensitivity, angular resolution, number of galaxies, and survey area.

The range of morphological types and masses available in galaxies within 25 Mpc, from tiny dwarf galaxies to giant elliptical galaxies, allows us to determine what effect these global galaxy properties have on the physical processes in the ISM and the resulting star formation. For example, higher pressure in the centers of spiral galaxies has been linked to increased density in the ISM (Helfer & Blitz 1993). With sufficient spatial resolution, we can study the effect of spiral arms or localized starbursts on the ISM, or the effect of metallicity in galaxies with radial metallicity gradients. Resolved observations of nearby galaxies also allow an important test of the reliability of using global measurements of galaxy luminosities to determine average physical properties. For example, comparing the dust temperature derived from a galaxy-wide average (cf. Regan et al. 2004) with the temperatures derived from many individual regions within the same galaxy provides a reality check on the methods we must use in distant, unresolved galaxies (cf. Wilson et al. 1999 for a similar test applied on the scale of individual giant molecular clouds). Thus, nearby galaxies provide a vital link between the detailed physics that can be probed in our own Galaxy and studies of more distant, unresolved galaxies, which are the only way to probe the long-term effects of galaxy evolution.

1.2 Specific science goals of the survey team

1.2.1 Physical properties of dust in galaxies

The data from this survey will play a key role in determining the physical properties of the various dust components (PAHs, very small grains, large grains) both in different regions within a single galaxy and also between galaxies. Understanding dust properties are important for obtaining accurate dust mass under a variety of environmental conditions and are also important for understanding the dust life cycle in galaxies (heating, spatial distribution of different components, destruction via shocks). The relative abundance and temperature of different types of dust grains are likely to vary with metallicity or the strength of the interstellar radiation field. For example, the spectral energy distribution (SED) of low-metallicity star-forming galaxies such as NGC 1569 (Lisenfeld et al. 2002, Galliano et al. 2003; Fig. 1) differs significantly from that of the Milky Way (Désert et al. 1990). These differences have been interpreted as evidence for a significant mass of very cold (7-10 K) dust in NGC 1569 (Galliano et al. 2003) or they may be the hallmark of extensive ISM processing of interstellar grains significantly modifying grain size and composition (e.g. Lisenfeld et al. 2004).

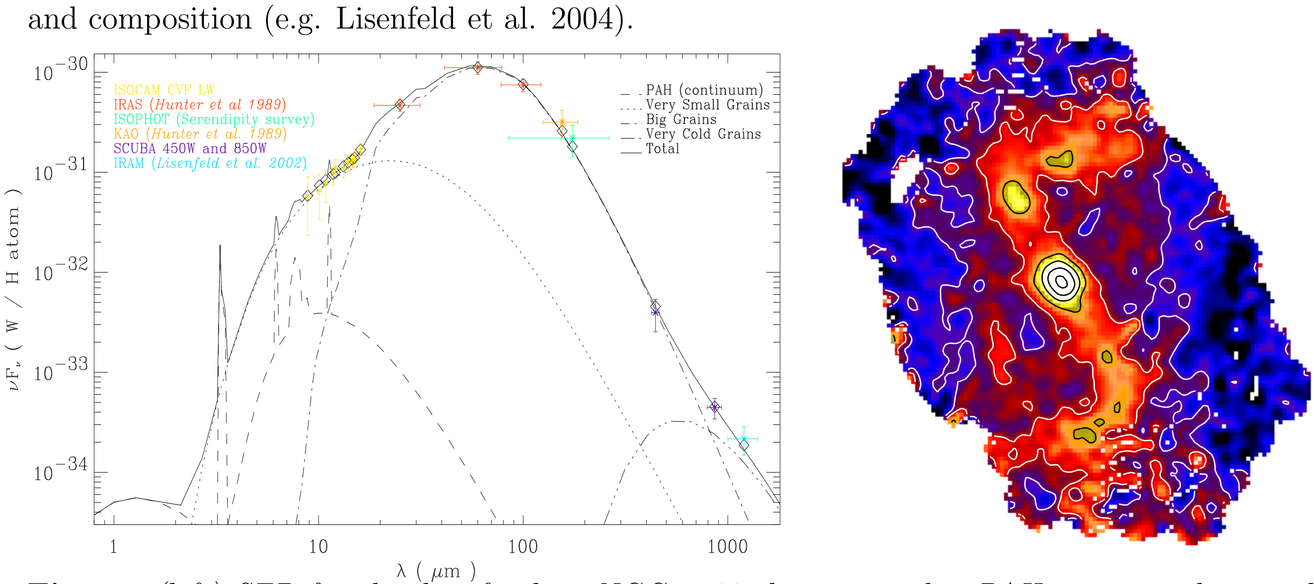

Fig. 1: *(left) SED for the dwarf galaxy NGC 1569 showing weaker PAH emission than in the Galaxy and possibly evidence at 850-1300 μm for a very cold dust component (Galliano et al. 2003). (right) SCUBA 850 μm image of the spiral galaxy NGC 2903 (Stevens et al. 2005).*

Determining the relative mass fraction of the different types of dust grains and constraining the physical properties of each component (size, temperature, composition) requires data that trace the full infrared-submillimetre spectral energy distribution. SCUBA-2 data at 850 and 450

μm are a key component for studying large and/or cold grains which usually contain most of the dust mass (Regan et al. 2004; Meijerink et al. 2005). Since it can be a large component of the total mass budget, there has been a renewed interest in determining whether very cold dust exists in galaxies (e.g. Neininger et al. 1996). Estimates of the gas to dust mass ratio from IRAS typically gave values 5-10 times larger than that of the Galaxy (Devereux & Young 1990). However, with a maximum wavelength of 100 μm, IRAS was not sensitive to dust with $T < 30$ K. More recent results from SCUBA suggest that very cold dust grains can be a large fraction of the total dust in galaxies (Alton et al. 2000, Dunne & Eales 2001). More sensitive submillimetre observations of a larger sample of galaxies will allow us to determine if such extremely cold dust is present in most galaxies.

Data in the mid- and far-infrared are necessary to trace the peak of the SED and the contribution from smaller dust grains which emit preferentially at shorter wavelengths. Full SED coverage can be obtained by combining data from this survey with data from BLAST, Herschel, and Spitzer (§1.4) and will allow self-consistent models of the dust components and the interstellar radiation field, which should settle the controversy over the presence of cold dust in galaxies. Measuring how rapidly dust properties (especially temperature) vary with position inside a galaxy (e.g. Walterbos & Schwering 1987) is important for quantifying the level of systematic error that may be incurred in studies of more distant systems for which only globally-averaged measurements are possible. It is important to note that the CO J=3-2 data are essential for accurate modeling of the dust continuum emission, since this line can contribute up to 25% of the total flux measured at 850 μm (Fig. 2).

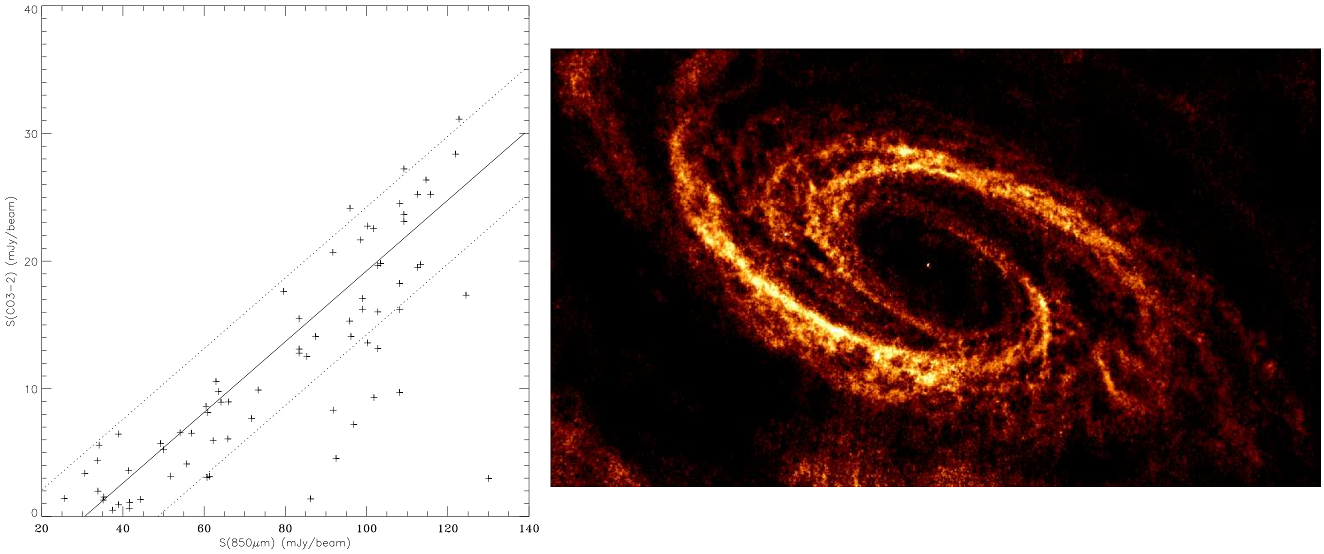

Fig. 2: *(left) Data for M51 showing the strength of the CO J=3-2 line compared to the 850 μm emission from SCUBA (Meijerink et al. 2005). The lines indicate the mean and range of CO/850 ratios; the contribution of the CO line to the SCUBA flux can be as large as 25%. (right) A VLA mosaic image of M81 in atomic hydrogen covering* $34 \times 20'$ *with a resolution of* $6''$ *illustrates the resolution and extent of the continuum and line images in our proposed survey. Image used with permission of the THINGS consortium (see de Blok et al. 2004 for details).*

1.2.2 Molecular gas and the gas to dust ratio

Molecular gas provides the fuel for star formation and so determining its physical properties and spatial distribution in a statistically well-selected sample of galaxies is a major aim of this survey. The only existing survey of similar size (300 galaxies, 236 detections) is the statistically inhomogeneous CO J=1-0 FCRAO survey (Young et al. 1995). Our proposed survey will significantly improve on the FCRAO survey in terms of resolution and angular coverage (e.g. Fig. 2), sensitivity, and statistical homogeneity. Our high-resolution data will allow us to compare the radial profiles of dust, HI, and CO *within* galaxies (e.g. Neininger et al. 1996). By using the CO J=3-2 line, our survey will be able to determine how frequently warm, dense molecular gas occurs in galaxy centers and disks. For example, at typical H_2 densities of 3000 cm^{-3}, the 3-2/1-0 ratio is 0.3 at $T_k = 10$ K, rising to 0.55 at 30 K and 0.95 at 150 K. Lower ratios are characteristic of the bulk of the unperturbed molecular gas, whereas higher ratios trace gas-accreting starburst nuclei and star-forming complexes in the disk (e.g. Devereux et al. 1994; Mauersberger et al. 1999). Recent results from the SMA illustrate clearly how J=3-2 emission traces the mechanical effects associated with nuclear or merger activity (Matsushita et al. 2004; Wang et al. 2004) or the radiative effects of starburst activity in the center of a galaxy (Iono et al. 2004).

The surface density of H_2 in a given region is commonly determined from CO lines by adopting a conversion factor X_{CO} (i.e. Strong et al. 1988). However, if we can determine accurate gas to dust mass ratios by detecting dust associated with HI (cf. Neininger et al. 1996), these can be combined with dust continuum observations to obtain an estimate of the H_2 column density independent of the CO line. More specifically, both $N(H_2)$ and the conversion factor X_{CO} can be determined independently by fitting the CO, HI, and dust SED data at every point in the galaxy where emission is detected and allowing the dust cross-section, σ, and X_{CO} to be factors determined in the fit (Braine et al. 1997). Such calculations can be particularly useful in unusual environments, such as low metallicity dwarfs or warm starbursts, where there is strong evidence that the relationship between CO brightness and H_2 mass deviates from the normal spiral relation both within and between galaxies (e.g. Wilson 1995; Braine et al. 1997; Israel & Baas 2003).

1.2.3 The effect of galaxy morphology

The larger-scale galaxy environment (pressure, hardness of radiation field, presence of an interaction or companion) may play a significant role in the properties and structure of the dense ISM which can only be identified with a sufficiently large sample of galaxies. For example, higher pressure in the centers of spiral galaxies has been linked to increased density in the ISM (Helfer & Blitz 1993). The overall pressure in low-mass dwarf galaxies is likely substantially lower than that in spiral disks (Young & Lo 1997). while the pressure due to the stellar component in giant ellipticals is clearly much larger. The interstellar radiation field, which is involved in heating the dust and gas, also varies substantially among these three types of galaxies. The intense stellar radiation field of elliptical galaxies is dominated by older, lower mass stars, although the presence of substantial X-ray halos in elliptical galaxies could have an impact on the heating of the dusty ISM. How these effects impact the structure of the ISM in ellipticals, which have relatively low column densities of gas and dust (Knapp et al. 1989, Bregman et al. 1998) as well as different sources of dust (Knapp et al. 1992, Tsai & Mathews 1995), is a question we can begin to address with this large survey. In spiral galaxies, the role of spiral arms in organizing and/or triggering star formation has been the subject of considerable debate (Elmegreen & Elmegreen 1986; Vogel et al. 1987). In the nearer galaxies in our sample, we will be able to look for differences in the dust properties between the arm and inter-arm regions (i.e. Alton et al. 2002), and see whether spiral shocks have the effect of producing a larger fraction of small grains (Jones et al. 1996).

CO rotation curves can be used to constrain the distribution of dark matter in the central parts of galaxies where HI emission is scarce and H_α is most likely to be affected by extinction. Thus, CO observations are important for assessing the prediction from Cold Dark Matter simulations that dark matter density profiles rise steeply in galaxy centres to form cusps. CO observations are also useful for determining velocities associated with central bars, which in turn may affect the evolution of a cusp (Athanassoula 2003). We can also determine the statistical occurrence of circumnuclear (R $<$ 500 pc) CO concentrations in galaxies to determine the timescales of formation and disruption of the nuclear gas concentrations which are thought to play an essential role in nuclear activity. In particular, the kinematic signature of rapidly-rotating circumnuclear material (velocity widths up to 400 km s^{-1}) can be used to estimate the dynamical mass and distinguish true (radially symmetric) central gas concentrations from distributions with double-peaks or even central holes that cannot be resolved spatially in our data (e.g. Israel, White & Baas 1995).

1.2.4 Unusual environments

a) Low-Metallicity Environments: This large sample of galaxies will allow us to probe the effect of metallicity on the properties and structure of the dense, dusty ISM. Low-metallicity regions are likely to have an ISM where the cold, dense regions traced by CO are much smaller and the warmer regions influenced by photodissociation are relatively larger than in solar-metallicity regions. These effects will be particularly important in dwarf galaxies (e.g. Madden et al. 1997), but could also be important in the outer disks of spiral galaxies that have steep metallicity gradients. Since the outer parts of spiral galaxies may differ from dwarf galaxies in aspects such as the strength of the interstellar radiation field and the average pressure, large galaxy samples are needed to disentangle these various effects. For example, comparing the properties and processes in a dwarf irregular galaxy with those in an outer region of a spiral galaxy with similar metallicity and star formation activity will reveal whether the larger-scale dynamical environment has a significant impact on the ISM.
b) Cluster membership: Galaxies in clusters experience a very different environment and are subject to a number of influences that do not affect galaxies in less dense environments. Many galaxy clusters contain substantial intra-cluster gas through which cluster galaxies move (cf. Young et al. 2002), which can result in the loss of a large fraction of their ISM through ram pressure stripping (Lee et al. 2003). Galaxies in clusters such as Virgo are found to be gas poor compared to similar galaxies in the field (the so called anaemic spirals, van der Bergh 1991). Cluster galaxies are also subject to rapid long-range gravitational interactions, both with other galaxies in the cluster and with the overall cluster gravitational potential, which may alter a galaxy's morphology as well as its rate of conversion of gas into stars (Moore et al. 1998). Many cluster members are early-type galaxies which IRAS and ISO generally failed to detect, likely either because their dust masses are too low or because the dust is too cool (there is no or little localized heating because of the lack of star formation). Only submillimetre observations, which are sensitive to the coolest dust that makes up the largest fraction of dust in galaxies, will be able discover how the dust cycle varies from one galactic environment to another.
c) Halos, Superwinds, and Nuclear Activity: Over a scale of a few hundred parsecs perpendicular to the disks of spiral galaxies, the large-scale environment changes dramatically from a dynamically cold disk with localized sources of hard UV radiation to a dynamically hot halo heated by a diffuse radiation field. Superwinds from galaxies with high star formation rates have been implicated as the origin of the mass-metallicity relation in the bulges of spirals, the source of

heating of the intergalactic medium (IGM) and the “pollution” of the IGM with heavy elements (Heckman 2003). High-latitude structures have been seen even in isolated galaxies with low star formation rates (e.g. Lee & Irwin 1997, Matthews & Wood 2003), while dust emission from galactic halos has been detected in a handful of systems (Neininger & Dumke 1999; Brar et al. 2003; Popescu et al. 2004). With the sensitive continuum data available from this survey, we will compare the dust distribution in the halos of edge-on galaxies to the locations of underlying star forming regions and compare the required energetics with the available energy from supernovae. For the galaxies in our sample which show signs of nuclear activity (either starbursts or AGN), we will also determine the effect of processes such as X-ray winds on the dusty ISM (Walter et al. 2002).

1.2.5 Luminosity and dust mass function

The discovery of a population of luminous dusty galaxies at high redshifts (Smail et al. 1997; Hughes et al. 1998) shows that there has been substantial cosmic evolution in the submillimetre properties of galaxies (Dunne et al. 2003). However, the amount of evolution is still uncertain because we do not yet have accurate measurements of the two most basic statistical descriptions of the submillimetre properties of the *local universe*: the space density of galaxies as a function of submillimetre luminosity (the luminosity function, LF) and of dust mass (the dust-mass function, DMF). We can measure these functions by observing a sample of galaxies drawn from statistically-complete samples selected in other wavebands and use accessible-volume techniques (Avni & Bahcall 1980) to make unbiased estimates of the LF and DMF. Dunne et al. (2000) presented the first estimates of the LF and DMF based on a single sample selected in the far-IR. Vlahakis et al. (2005) made estimates of the LF and DMF based on the original sample and on a sample selected in the optical waveband. However, the LFs and DMFs based on two samples are a factor of 2-3 higher than the original estimates based on the far-IR sample alone. This increase occurs because the optically-selected sample contains many galaxies with cold dust, of which there are no representatives at all in the original far-IR selected sample. In addition, since the SLUGS sample included only galaxies more distant than 25 Mpc (Dunne et al. 2000), this survey was limited to galaxies with high luminosities. While Planck will make an all-sky survey, its large beam ($5'$) and higher noise (19 mJy/beam at 850 μm) means it will be most sensitive to distant, luminous galaxies and so will probe primarily the high-mass end of the luminosity function. By making more sensitive observations of galaxies above an HI flux limit that are outside the Local Group, we will detect galaxies with luminosities $\sim$ 100 times lower than the lowest luminosities detected in the Dunne et al. (2000) sample.

1.3 Sample Selection and Sample Size

We have identified in the HyperLeda database all galaxies with HI detections having Virgo-corrected galactocentric velocities $v < 1875$ km/s corresponding to distance closer than 25 Mpc (for $H_o = 75$ km/s/Mpc) and declination greater than -25^o. Out to these limits, the HyperLeda database is essentially complete. By using HI flux as a discriminator, we have ensured that (1) the sample selection is directly based on the amount of interstellar matter present in a galaxy, and (2) the sample is not unduly biased by the dust being either hot or cold, and so this sample should be rather more representative of the local submillimetre universe than previous samples (e.g. Dunne et al. 2000). From this sample, we removed all galaxies closer than 2 Mpc (i.e. the Local Group), and all galaxies with Galactic latitudes between -25^o and 25^o. (Although the impact of noise from Galactic cirrus is negligible at 850 μm over most of the sky, it can be a significant problem at the mid- and far-infrared wavelengths probed by Spitzer, Herschel and BLAST. Since comparison with infrared data will strengthen the scientific return and legacy value of this survey, we have chosen to apply a stricter latitude cutoff than is required by the SCUBA-2 observations alone.) These selection criteria gave us a sample of 1002 field galaxies and 148 Virgo cluster galaxies (galaxies within an 8×16^o ellipse centered on M87 (RA=12.4^h, DEC=12.4^o) and with velocities between 500 and 2500 km s^{-1}, e.g. Davies et al. 2004).

We estimate that roughly 1500 hours of telescope time would be required to observe this complete sample of 1150 galaxies. We thus turned our attention to the question of what is the minimum sample size that would allow us to answer the scientific questions in this study and arrived at a sample size of 300 galaxies based on the following arguments. For the statistical studies of galaxy properties, we will want to divide the galaxies into 4 morphological bins (E/S0, early-type spirals, late-type spirals, and irregulars) and two luminosity bins (bright and faint). In addition, we want to compare the properties of galaxies in the Virgo cluster to those in the field, giving us a total of $4 \times 2 \times 2 = 16$ bins. To obtain good statistics on the average properties of each bin we feel requires 25 galaxies in each bin or 400 galaxies total. However, since our sample only contains 148 Virgo galaxies, we compromise on 12-13 galaxies per bin in Virgo and 25 per bin in the field, giving a total sample size of 300 galaxies.

To select the final sample, the field and Virgo lists were each divided into the four morphological bins described above using the t parameter. For the field samples, we first applied an HI flux cutoff of 3.3 Jy km s^{-1}, which reduced the list from 1002 to 902 galaxies, and then randomly selected 50 galaxies in each of the four morphological bins. The smaller Virgo sample meant that we could only use this same process for the late-type spiral bin. All E/S0 (24) and Irr (25) galaxies from Virgo were included, and the 25 brightest early-type spirals (with HI flux $>$ 3 Jy km s^{-1}) were included. The final sample includes 12 of 44 galaxies from SINGS and 29 of 119 galaxies from the IRAS RBGS. Finally, we added the remaining SINGS galaxies (see § 1.1) that meet our distance and other selection criteria to obtain a final sample of 331 galaxies. The resulting source lists can be viewed at

`http://physwww.physics.mcmaster.ca/~wilson/www_xfer/LU_sample331/`

1.4 Synergies with other surveys

The proposed local universe survey will have substantial synergies with other infrared and radio surveys currently planned or in progress. The availability of infrared data substantially strengthens the science that can be gained from the JCMT survey, since coverage of the spectrum from mid-infrared through submillimetre wavelengths is required to determine the properties and relative amounts of the different dust components in galaxies (Galliano et al. 2003, Regan et al. 2004). The SINGS survey (Kennicutt et al. 2003) is a Spitzer Legacy survey which consists of photometric and spectroscopic observations from 3 to 160 μm of a heterogeneous sample of 70 nearby galaxies. In addition, there is another large Spitzer survey (PI: Alexander) of galaxies from the IRAS RBGS (Sanders et al. 2003). THINGS, the HI Nearby Galaxy Survey (de Blok et al. 2004), is a large project on the VLA which will observe the 40 nearest SINGS galaxies in B, C, & D array with 5" and 5 km s^{-1} resolution.

Some of the most important overlap is with planned Key Projects with the Herschel Space Observatory. For example, the science team for the SPIRE instrument is considering three different surveys that are relevant here: a survey of about 50 nearby dwarf galaxies; a complete and detailed survey of 15 very nearby galaxies spanning a range of galaxy morphologies; and a K-band selected survey of roughly 400 galaxies within 25 Mpc. The parameters of these three surveys are still being worked out, but the substantial overlap of members between the SPIRE science team and the Co-Is on the current proposal will allow for maximum co-ordination between the galaxy lists. The SPIRE and PACS instruments on Herschel and SCUBA-2 on the JCMT are extremely complementary instruments; SCUBA-2 is critical to identifying the presence of a very cold dust component in galaxies (see Fig. 1), while the Herschel instruments provide photometric data at 60-550 μm which probe the peak of the dust spectral energy distribution. In the shorter term, the BLAST camera is a SPIRE prototype (same filters, detectors etc.) that will fly in May 2005. With a 2 m prototype, it will have twice the beam of Herschel but significantly better resolution than data from ISO or IRAS, and will provide data at 250, 350, and 550 μm that will be unique in terms of wavelength coverage until Herschel is launched in 2007.

References:

• Alton, Xilouris, Bianchi, et al. 2000, A&A, 356, 795 • Alton, Bianchi, Richer et al. 2002, A&A, 388, 446 • Athanassoula E. 2004, IAU Symp 220, ed. S. Ryder, D.J. Pissan, M. Walker, & K.C. Freeman, 255 • Avni, & Bahcall, 1980, ApJ, 235, 694 • Braine, Geulin, Dumke et al. 1997, A&A, 326, 963 • Brar, Irwin, & Saikia, 2003, MNRAS, 340, 269 • Bregman, Snider, Grego, & Cox 1998, ApJ, 499, 670 • Davies, Minchin, Sabatini, et al. 2004, MNRAS, 349, 922 • de Blok et al. 2004, astro-ph/0407103 • Désert, Boulanger, & Puget 1990, A&A, 237, 215 • Devereux & Young 1990, ApJ, 359, 515 • Devereux et al 1994 ApJ, 107, 2006 • Dunne & Eales, 2001, MNRAS, 327, 697 • Dunne, Eales, & Edmunds, 2003, MNRAS, 341, 589 • Dunne, Eales, Edmunds, et al. 2000, MNRAS, 315, 115 • Elmegreen & Elmegreen, 1986, ApJ, 311, 554 • Galliano, Madden, Jones, et al. 2003, A&A, 407, 159 • Heckman, 2003, in "Galaxy Evolution: Theory and Observations", eds. Avila-Reese, Firmani, Frenk, et al., RMAA. Conf. Series, 17, 47 • Helfer & Blitz 1993, ApJ, 419, 86 • Hughes, et al. 1998, Nature, 394, 241 • Iono et al. 2004 ApJL 616, L63 • Israel & Baas, 2003, A&A, 404, 495 • Israel, White & Baas 1995 A&A 302, 343 • Johnstone et al., 2001, ApJ, 559, 307 • Jones, Tielens, & Hollenbach 1996, ApJ, 469, 740 • Kennicutt, Armus, Bendo, et al. 2003, PASP, 115, 928 • Knapp, Guhathakurta, Kim, & Jura 1989, ApJS 70, 329 • Knapp, Gunn, & Wynn-Williams 1992, ApJ, 399, 76 • Kroupa, 2002, Science, 295, 82 • Lada, Bally, & Stark, 1991a, ApJ, 368, 432 • Lada, Evans, Depoy, & Gatley 1991b, ApJ, 371, 171 • Lee, & Irwin, 1997, ApJ, 490, 247 • Lee, McCall, & Richer 2003, AJ, 125, 2975 • Lisenfeld, Israel, Stil & Sievers, 2002, A&A 382, 860 • Lisenfeld, Israel, Stil, et al. 2004, astro-ph/0412474 • Madden, Poglitsch, Geis, et al. 1997, ApJ, 483, 200 • Matsushita et al. 2004 ApJL 616, L55 • Matthews, & Wood, 2003, ApJ, 593, 721 • Mauersberger et al. 1999 A&A 341, 256 • Meijerink, Israel, Tilanus et al., 2005, A&A, 430, 427 • Moore, et al., 1998, ApJ, 495, 139 • Motte, André, & Neri, 1998, A&A, 336, 150 • Neininger, & Dumke, 1999, PNAS, 96, 5360 • Neininger, Guélin, Garcia-Burillo et al., 1996, A&A, 310, 725 • Popescu, Tuffs, Kylafis, et al., 2004, A&A, 414, 45 • Regan et al., 2004, ApJS, 154, 204 • Sanders, Mazarella, Kim, et al. 2003, AJ, 126, 1607 • Smail, Ivison, & Blain, 1997, ApJ, 490, L5 • Stevens, Amure, & Gear 2005, MNRAS, 357, 361 • Strong et al. 1988, A&A, 207, 1 • Tsai & Mathews 1995, ApJ, 448, 84 • van der Bergh, 1991, PASP, 103, 390 • Vlahakis, Dunne, & Eales, 2005, MNRAS, submitted • Vogel, Kulkarni, & Scoville, 1987, Nature, 334, 402 • Walter, Weiss, & Scoville, 2002, ApJ, 580, L21 • Walterbos & Schwering 1987, A&A, 180, 27 • Wang et al. 2004 ApJL 616, L67 • Wilson 1995, ApJ, 448, L97 • Wilson, Howe, & Balogh, 1999, ApJ, 517, 174 • Young & Lo, 1997, ApJ, 490, 710 • Young & Scoville 1991, ARAA, 29, 581 • Young et al. 1995 ApJS 98, 219 • Young et al., 2002, ApJ, 579, 560

2 Technical Justification: SCUBA-2 and HARP-B

We plan to map all the galaxies in our sample with SCUBA-2 out to D_{25} to a 1σ limit of 1 mJy at 850 μm; we estimate that the high-redshift extragalactic background will increase the actual noise level to 1.3 mJy. To convert this sensitivity to an equivalent mass surface density (gas plus dust), we use the formula given in Johnstone et al. (2001) and assume $T_{dust} = 20$ K, $\kappa_{850} = 0.01$, and a circular beam with diameter $15''$. With these assumptions, we will be able to obtain 4σ detections of regions with 0.78 A_v, which corresponds to 1.6×10^{21} H/cm^2 or 12 M$_\odot$/pc^2. The time required to map an area of 1 square degree to 1 mJy rms is 20.7 hours. However, many of the galaxies in our sample fit within a single SCUBA field of view. We estimate that 0.5 hours is required to observe a single SCUBA-2 field of view (a "jiggle map") to this rms level.

Good 450 μm data are essential to tracing the deflection in the SED indicates the presence of very cold dust or a change in dust properties (see Fig. 1). Thus, 450 μm data are crucial for obtaining an accurate estimate of the total dust mass as well as for clarifying the relative distributions of the different types of dust (§1.2.1). (While we might be able to compensate for a lack of 450 μm data by adding data from Herschel, the resolution in the critical wavelength region would be lower ($36''$ at 550 μm), and Herschel may not be able to observe our entire sample.) The 1σ noise in the 450 μm images with $8''$ resolution will be 10 mJy. Assuming the dust emissivity has $\beta = 1.5$, a given region will be 6 times brighter at 450 μm than at 850 μm. Thus, for an extended source, the mass sensitivity in the two maps smoothed to the same resolution is comparable.

With HARP-B, we are aiming to map out to $D_{25}/2$ with a 1σ noise level in the integrated CO J=3-2 intensity of 1.2 K km s^{-1}. Assuming $X(CO) = 2 \times 10^{20}$ H$_2$ cm^{-2} (K km s^{-1})$^{-2}$, a typical J=3-2/J=1-0 ratio of 0.5 and including a factor of 1/0.63 to convert from T_A^* to T_{MB}, our 3σ upper limit corresponds to 2.6×10^{21} H$_2$/cm^2 or $A_v = 2.6$ (roughly three times larger than our planned SCUBA-2 sensitivity). The 1σ integrated intensity is given by $\Delta T\sqrt{\Delta V \delta V}$ where ΔT is the temperature rms in a single channel of width δV and the galaxy linewidth is ΔV. If $\Delta V = 200$ km s^{-1} for a typical galaxy and $\delta V = 40$ km s^{-1}, we would need $\Delta T = 13$ mK. (Note that the sensitivity will be better for galaxies with narrower lines.) The time required to map a $10 \times 10'$ area with 40 MHz frequency resolution and system temperature of 500 K to a 1σ noise per channel of 13 mK is 11.6 hours. To estimate the time required to observe a single HARP-B footprint, we use $\Delta T = kT_{sys}/\sqrt{\Delta\nu\Delta t}$ with $k = 1.7$ (Dent, priv. comm). For the same system temperature, resolution, and temperature rms used in the scan map estimate, the time required is 107 s per position or 30 minutes to observe the 16 positions required to obtain a fully sampled $2 \times 2'$ map.

Our random sample consists of 259 galaxies small enough ($D_{25} < 5'$) to fit inside the SCUBA-2 field of view plus 40 galaxies covering a total area on the sky of 0.49 square degrees. The 32 additional SINGS galaxies include 7 small galaxies and 25 large galaxies covering 0.41 square degrees. Thus, the SCUBA-2 integration time for the random sample is 129.5 hr for the small galaxies and 10.2 hr for the large galaxies, while the corresponding times for the SINGS sample are 3.5 hr and 8.5 hr, for **a total time of 152 hours of grade 1-2 weather.** Because HARP-B requires much longer integration times than SCUBA-2 to map a given area, we plan to map our large galaxies out to $D_{25}/2$ and our small galaxies with a single HARP-B field. Thus, the estimated HARP-B integration time for the random sample is 129.5 hr for the small galaxies and 51 hr for the large galaxies, while the corresponding times for the SINGS sample are 3.5 hr and 43 hr, for **a total time of 227 hours of grade 3 or good grade 4 weather** ($\tau_{CSO} < 0.15$).

3 Management

The team will make major decisions by consensus whenever possible; however, if no consensus can be reached, the three co-ordinators (see pg. 1) will make the final decision. The co-ordinators are also empowered to make decisions on questions requiring a rapid response and are responsible for managing the survey, including making sure the telescope is staffed properly, deciding on foreign participation in the survey, adjudicating any authorship conflicts, etc. The team will also appoint two archive representatives who will be responsible for liaising with the archive developers and for certifying the quality of the data products once the survey is underway.

Survey membership will remain open to researchers from the three partner countries until data taking begins. This will make it easy for new faculty members, postdocs, and students to join the survey. Individual requests to join the survey from researchers outside the three partner countries will be considered on a case-by-case basis; we propose that foreign members can also be added until data taking begins. Membership in this survey implies a commitment to provide experienced people to go observing. There are 17 institutions involved in this survey; allowing for overhead due to bad weather, the average observing commitment per institution will be about 4 nights. This level of staffing is easily covered by the Co-Is and their students and postdocs. We will designate one representative per institution and that person will be the primary point of contact for the survey, including making sure that the institution's observing share is covered.

The team will develop a written publication policy within 3 months. There will be a few initial papers from the survey which will include the entire survey team as co-authors. Authorship of subsequent papers will be on the principle that work earns authorship, where "work" includes doing useful observing. For subsequent papers, the co-ordinators will maintain a list of "papers in preparation" and any survey member is allowed to join in the work (with the exception of student theses, which will have a restricted authorship list). Access to all data from the survey will remain open to all survey members, regardless of whether the data is currently being analyzed for a particular paper. The coordinators are responsible for resolving any conflicts.

To enable early publication of some results from this survey, we will select a high-priority subset of one-third of the galaxies from our total sample to be observed first. This subset of galaxies will include all galaxies in our sample for which complementary data from other facilities such as Spitzer are available and will include both small and large galaxies so that we can test all our planned observing modes. (Note that at least half the HARP-B observations can be started simultaneously with the SCUBA-2 observations i.e. SINGS galaxies, known gas-rich spirals, etc.) We plan to make the data for this high-priority subset publicly available two years after the start of the survey, i.e., one year earlier than the advertized proprietary time for JCMT legacy surveys.

The primary data products produced in this survey will be 850 and 450 μm images for 331 galaxies and CO data cubes for most of these galaxies (see next section). For 266 of the galaxies, the images and data cubes will be obtained on a single night, and so little or no additional processing beyond the basic pipeline may be needed to produce a final science-quality image. For the CO data, it will probably be necessary to remove a baseline from the spectra to produce the final integrated intensity data cube. It is desirable that this baseline removal be part of the basic pipeline processing provided at the JAC. For some of the 65 large galaxies, it may be necessary to combine raster maps (with either SCUBA-2 or HARP-B) taken on two or more nights. It is desirable that pipeline processing that can create a master image from data taken on multiple nights be developed at the JAC.

4 Legacy value of a local universe survey

The proposed survey will measure the submillimetre continuum and CO J=3-2 emission from a sample of 331 galaxies. This will be a statistically well-selected sample chosen on the basis of detected HI emission and a distance of no more than 25 Mpc. From that complete sample, we have chosen a random subset of galaxies such that the average properties of the subset match the properties of the complete sample. To this sample, we have added the 32 SINGS galaxies that meet our distance and other selection criteria. This survey will produce the first large sample of galaxies observed with good spatial resolution at submillimetre wavelengths. The scientific return from this project will be a solid understanding of properties of dusty ISM in galaxies and how those properties are affected by their environment, both internal (spiral arm, metallicity) and external (galaxy morphology, cluster membership), as well as a good measurement of the submillimetre luminosity function and dust mass function. The images and catalogs that will be produced from this survey will serve as a valuable path-finder for concurrent and future instruments such as Herschel, SOFIA, LMT, ALMA, and JWST.

We plan to produce the following 5-7 data products from this survey:

1. images at 850 and 450 μm for 331 galaxies within 25 Mpc
2. CO J=3-2 integrated intensity images for the subset observed in CO (see below).
3. CO J=3-2 data cubes for that same subset of galaxies
4. estimate of CO J=3-2 flux for this same subset of galaxies; both observed flux and an estimate of the global flux extrapolated to D_{25} from a radial average will be provided
5. catalog of galaxy fluxes at 850 and 450 μm for 331 galaxies; also an estimate of the 850 μm flux corrected for CO J=3-2 contamination
6. (desirable) map of the 850/450 ratio for 331 galaxies (including proper cross-calibration calibration, matching of error beams, etc.)
7. (desirable) 850 μm image corrected for CO 3-2 contamination, with detailed notes on how CO contamination was obtained (e.g. directly from CO 3-2 data; extrapolated from CO 3-2 data in other parts of the same galaxy; extrapolated from CO 3-2 data from another galaxy of similar type)

We will make our target list public so that a future user of the JCMT (or other telescopes) will know which galaxies are present in our sample and if so, what area will be mapped with SCUBA-2 and HARP-B. For the HARP-B observations, the target list will clearly indicate which of the galaxies in our sample are certain to be observed (i.e. those with previous CO and/or submillimetre detections) and over which areas of the galaxy. For the remaining galaxies, CO observations may only make sense if the galaxy is detected with SCUBA-2. For these galaxies, we will describe our selection criteria and mapping strategy and will update the HARP-B target list on a monthly basis as the availability of SCUBA-2 data allows us to decide whether or not a given galaxy will be mapped with HARP-B.

5 Justification of non-partner members

Colin Borys is a Canadian citizen who is currently a postdoctoral fellow at Caltech. He has accepted a postdoctoral fellowship at the University of Toronto beginning August 1, 2005.

Glen Petitpas is a Canadian citizen who is currently a postdoctoral fellow (October 2004-September 2007) with the Submillimeter Array in Hilo, Hawaii. Additionally, he has ties with the upcoming CARMA array, a project in which he was involved during his postdoc at the University of Maryland. Thus, he brings the possibility of access to the SMA (and eventually CARMA) for high-resolution follow-up observations of particularly interesting individual galaxies from the sample. Scientifically, Glen adds to existing expertise in spiral galaxies and dwarf galaxies; his Ph.D. thesis at McMaster University was based on heterodyne JCMT observations of nearby galaxies and analysis of spectral line ratios. Currently based in Hilo, he can easily participate in observing and is experienced with the JCMT. Glen plans to return to Canada after his postdoc at the SMA, which, on the current schedule, would be sometime before this survey is completed.

David Hughes is based at INAOE in Mexico, where he is the project scientist for the Large Millimeter Telescope (LMT), a 50 m diameter single-dish millimetre-wave telescope designed for principal operation at wavelengths between 1mm and 4mm. Scientific operation of the LMT will begin in 2007. He is also a member of the instrument team for AzTEC, a 1.1 mm 144-pixel continuum camera that is ultimately destined for the LMT and will be commissioned on the JCMT in June 2005. When installed on the LMT, AzTEC will have a mapping speed and angular resolution at 1.1 mm that is comparable to that of SCUBA-2. Complementary data from the LMT at 1.1 mm would be a very useful addition to the science of this survey. The LMT will also have a number of spectral line cameras that will provide complementary data to the HARP-B data proposed here. David is also a co-investigator with BLAST, where he has been leading the effort to use it to observe nearby galaxies. BLAST is a NASA funded experiment that will conduct confusion-limited extragalactic and Galactic surveys at 250, 350 and 500 μm from a long-duration balloon-borne platform. BLAST will fly a 2-m primary mirror during a series of long-duration balloon (LDB) science flights from 2005 onwards.