The Spatial Distribution of Cold Dust in Nearby Galaxies

J. L. Hinz[1], C. W. Engelbracht[1], C. N. A. Willmer[1], G. H. Rieke[1], M. J. Rieke[1], P. S. Smith[1], M. Blaylock[1], K. D. Gordon [1,2], the M 31 and M 33 MIPS GTO Teams

ABSTRACT

We present results from the *Spitzer* MIPS instrument regarding the spatial distribution of cold dust emission in a variety of nearby galaxies. Large masses of cold dust can be observed surrounding objects of varying physical size and morphological type, including galaxies quite low in mass. In several cases, the cold dust emission represented by the MIPS 160 μm images extends beyond the optical and near-infrared disks of galaxies. The amount of detectable cold dust emission is likely dependent on the amount of diffuse, nonionizing ultraviolet photons produced by the young stellar population. Therefore, many more galaxies with lower rates of star formation may have large amounts of very cold dust that escape detection. The existence of such cold dust halos allows us to probe issues regarding the assembly, storage, and retention of dust in disk galaxies and to better understand how the dust interacts with its environment. For instance, tracing gas-to-dust ratios far into disks allows us to distinguish between methods of dust production and transportation, and comparing with other wavelengths enables us to locate the sources of dust heating.

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure

1. Introduction

Spiral galaxies, including our own, contain large masses of dust at cold (T=15-20 K) temperatures (e.g., Reach et al. 1995; Lagache et al. 1998). This cold component has been demonstrated to be the most massive, accounting for up to 80% of the total dust mass in normal galaxies (Sauvage et al. 2001) and even in dwarfs (Galliano et al. 2003; 2005; Madden et al. 2005), where it had been assumed that little or no dust was retained. It has

---

[1] Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson AZ 85721

[2] Space Telescope Science Institute, 3700 San Martin Way, Baltimore MD 21218

been shown that halos of this cold dust can exist beyond the traditional optical extent of galaxies, reaching into the outer H I gas (e.g., Tuffs & Popescu 2005), which raises a number of questions regarding the origin and heating of the dust.

For example, the presence of these cold dust halos challenges standard steady state models of dust formation/production in AGB stars and destruction by grain sputtering in the hot ISM because of the large galactocentric distances at which the dust is found. If the dust is all formed in evolved stars in the optical disk, then a method of non-destructively transporting the dust to the outer reaches is needed (e.g., outflows from the galaxy nucleus), or we must attribute its existence to an interaction with another galaxy.

Thus far, however, observations imply that extended cold dust envelopes are not universal, and currently there is no explanation for why some galaxies have detectable levels of outer disk cold dust while others do not. Spectral energy distributions (SEDs) of the SINGS Legacy galaxies have shown that only a small number have significant amounts of cold dust with 160 to 70 μm flux ratios in excess of 5 (Dale et al. 2005). Recent work using IR and submillimeter data for SINGS galaxies (Draine et al. 2007) has shown that dust models do not require the presence of very cold dust ($T<10$ K) and that cold dust grains in dark clouds contain <50% of the total dust mass. However, SINGS observations are shallow in depth, perhaps missing the most diffuse dust component. SINGS objects were selected partially on *IRAS* properties and, due to the wavelength limit of 100 μm on *IRAS*, may be biased against objects with large amounts of extended cold dust.

To address these issues, the MIPS GTO team is conducting a coordinated study of cold dust emission in nearby galaxies, concentrating on MIPS 160 μm imaging of objects with a range of morphological types, including M 31, M 33, M 101, NGC 205, dwarf galaxies, and low surface brightness galaxies. Preliminary results show diffuse cold dust stretching beyond the traditional optical disks of several galaxies.

2. Observations of Extended Cold Dust

One of the first objects detected with *Spitzer* MIPS recognized to have an extended cold halo at 160 μm was NGC 55, a dwarf member of the Sculptor group (Engelbracht et al. 2004). Early scan-map observations taken during MIPS engineering time showed extended 160 μm along both the major and minor axes of the galaxy when compared with 24 and 70 μm, as shown in Figure 1a. This is not simply a result of the resolution difference between the wavelengths; all wavelengths are convolved to the 160 μm resolution.

Another dwarf, UGC 10445, an SBc starbursting galaxy at 15 Mpc (van Zee 2000), was

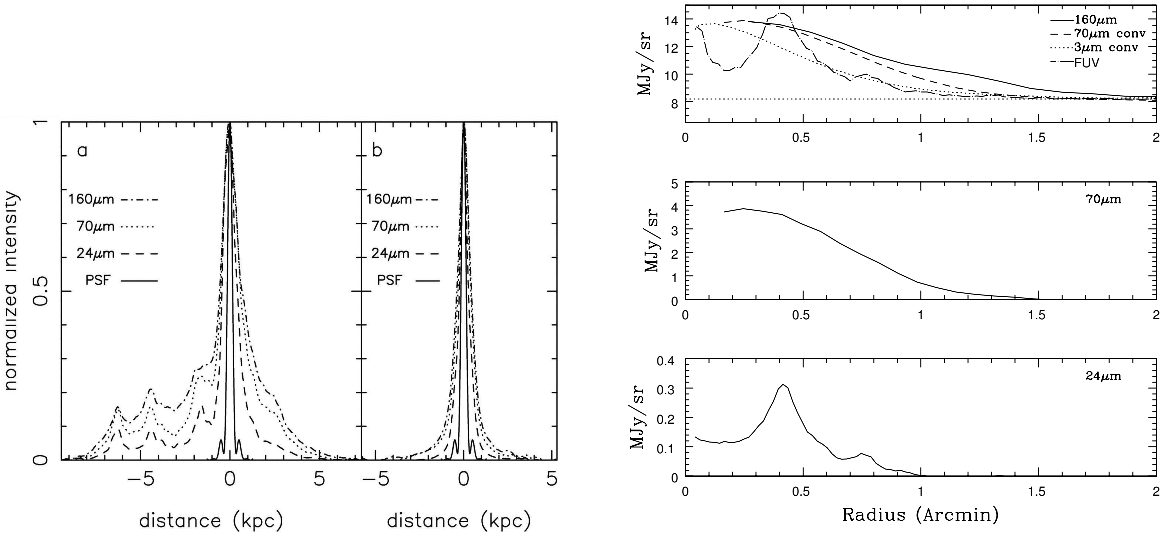

Fig. 1.— *Left*: major and minor axis surface brightness profiles of NGC 55, with all three wavelengths convolved to the 160 μm resolution and normalized to the same intensity (from Engelbracht et al. 2004). *Right*: azimuthally averaged radial profiles of UGC 10445 at all three MIPS wavelengths. The top panel also includes profiles at far-UV wavelengths from *GALEX* (Martin et al. 2005) and at IRAC's 3.6 μm band.

imaged in MIPS photometry mode in search of cold dust. The IR SED for this galaxy, including *ISO*, MIPS, and *IRAS* data points, was fitted by two modified blackbodies and revealed to have a large cold (T=18 K) dust mass component of over $10^6 M_\odot$ (Hinz et al. 2006). Additionally, azimuthally averaged radial profiles of the galaxy show that its 160 μm emission has a distinctive bump at $1\farcm2$ and extends an arcminute beyond the emission of the galaxy at other wavelengths. The cold dust component extends beyond both the young stellar population, represented by *GALEX* UV emission, and the old stellar population, represented by IRAC 3.6 μm emission (see Figure 1b).

This trend of having extended cold dust emission appears to hold for larger galaxies as well, such as M 33 and M 31. Exceptionally deep images of M 33, with four epochs of MIPS scan data at 160 μm (e.g., Tabatabaei et al. 2007), reveal that the emission at 160 μm extends further than the other two MIPS wavelengths. The MIPS scan map of M 31, covering the entire $1^\circ \times 5^\circ$ H I disk of the galaxy, shows 160 μm emission associated with the cold dust component that does not appear to drop to the level of the background, particularly on one side of the galaxy. Figure 2 shows the 160 μm image of M 31 with the H I map (courtesy Braun & Thilker) as well as a cut through the galaxy at the three MIPS wavelengths. The problem of extended 160 μm in M 31 is complicated, however, by foreground cirrus emission from the Milky Way. Future work will use an existing H I column density mosaic of the Galactic foreground created from WSRT and GBT survey data to scale the H I cirrus by an assumed dust emission SED and subtract from the M 31 map to obtain a map as foreground free as possible.

These extended cold dust disks beyond the traditional optical extent of galaxies are even more intriguing given recent work in the optical and UV that suggests that galaxy disks at those wavelengths are larger than was generally thought (e.g., Zartisky & Christlein 2007; de Jong et al. 2007).

3. Exploration of Dust Heating Sources

Sources for heating this cold dust component have been explored, among other works, for spirals in the Virgo cluster by Popescu et al. (2002). Their proposal is that the cold dust is predominantly heated by the diffuse nonionizing UV radiation produced by the young stellar population, with a smaller contribution to the dust heating coming from the optical radiation produced by old stars. This proposal appears to be consistent with model predictions (Popescu et al. 2000; Misiriotis et al. 2001). The UV flux needed to heat the dust grains to the temperatures predicted by blackbody fits to, for example, UGC 10445 (Hinz et al. 2006), is not very large, and a sufficient amount of UV radiation leaking from star

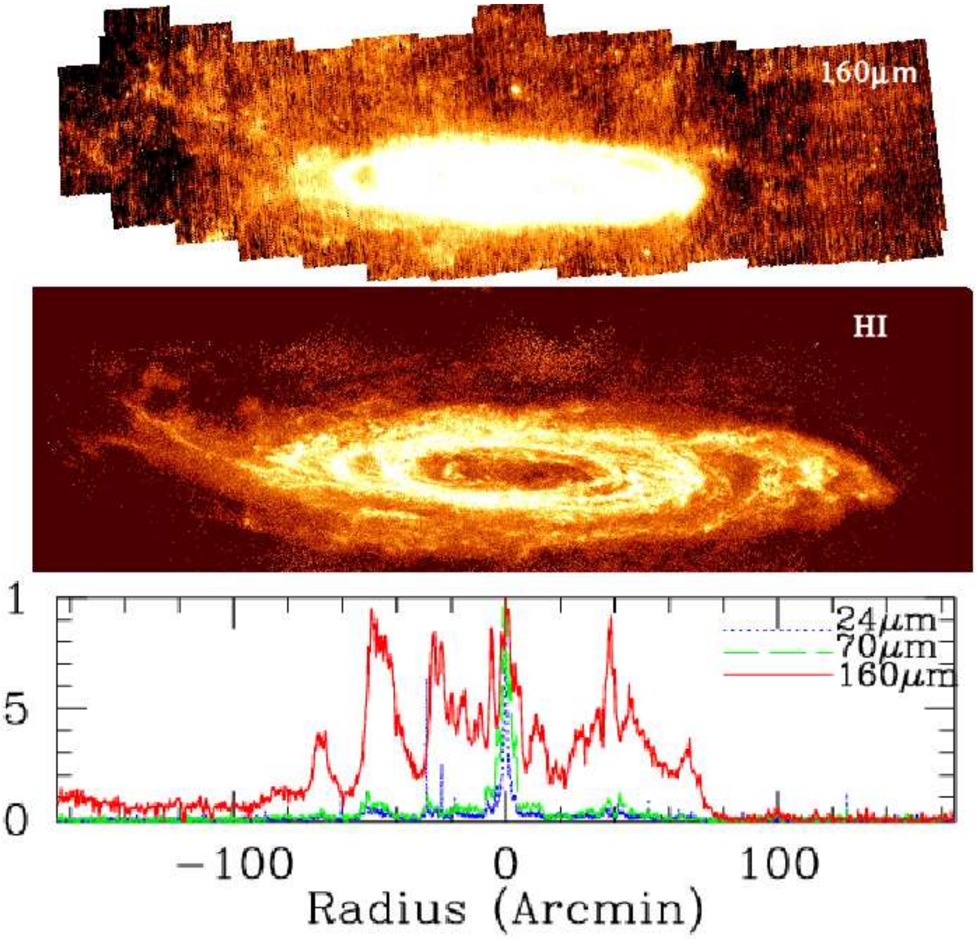

Fig. 2.— MIPS 160 μm (*top*) and H I (*middle*) images of M 31 covering 1 ° × 5 °. *Bottom*: A cut through M 31 at all three MIPS wavelengths showing the extended 160 μm emission.

formation complexes could be the source of the heating.

One way of testing the young stellar population as the main source of dust heating is to obtain MIPS images of low surface brightness galaxies (LSBGs), where star formation rates are known to be low. If a certain threshold of UV photons is needed to detect cold dust emission at 160 μm, low surface brightness disks would likely not show detectable emission in the far-IR. Recent *Spitzer* observations of a small sample of LSBGs (Hinz et al. 2007) show that, while all are detectable at the IRAC wavelengths, very few exhibit emission beyond 24 μm. The galaxies that do show emission at 70 and 160 μm are also generally the ones that have the most obvious extended 24 μm features. More quantitatively, as shown in Figure 3, galaxies with high central surface brightnesses in the B-band have lower 24-to-160 μm flux densities.

4. Summary

Galaxies of many varieties have a diffuse cold dust component, including large high surface brightness disk galaxies, dwarfs, irregulars, and some low surface brightness galaxies. The cold dust components in some of these galaxies detected by MIPS at 160 μm extend beyond their traditional optical disks. The source of the cold dust heating is likely to be diffuse UV photons leaking from star forming regions in the galaxy, with a smaller contribution of optical radiation from the old stellar population. It is possible that all or most galaxies have a diffuse dust halo, but this may not be visible at the MIPS wavelengths if there is little star formation activity producing the necessary heating via non-ionizing UV photons.

5. Future Work

Deep MIPS multi-scan observations of a small sample of nearby galaxies have been obtained in *Spitzer* Cycle 3 and are being analyzed for cold dust content, including re-observations of NGC 55 and UGC 10445. Additionally, a sample of very faint isolated dwarf irregulars (e.g., van Zee 2000) are being observed currently in Cycle 4. These data will allow us to understand cold dust emission in a wide range of morphological types.

This work is based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory (JPL), California Institute of Technology under NASA contract 1407.

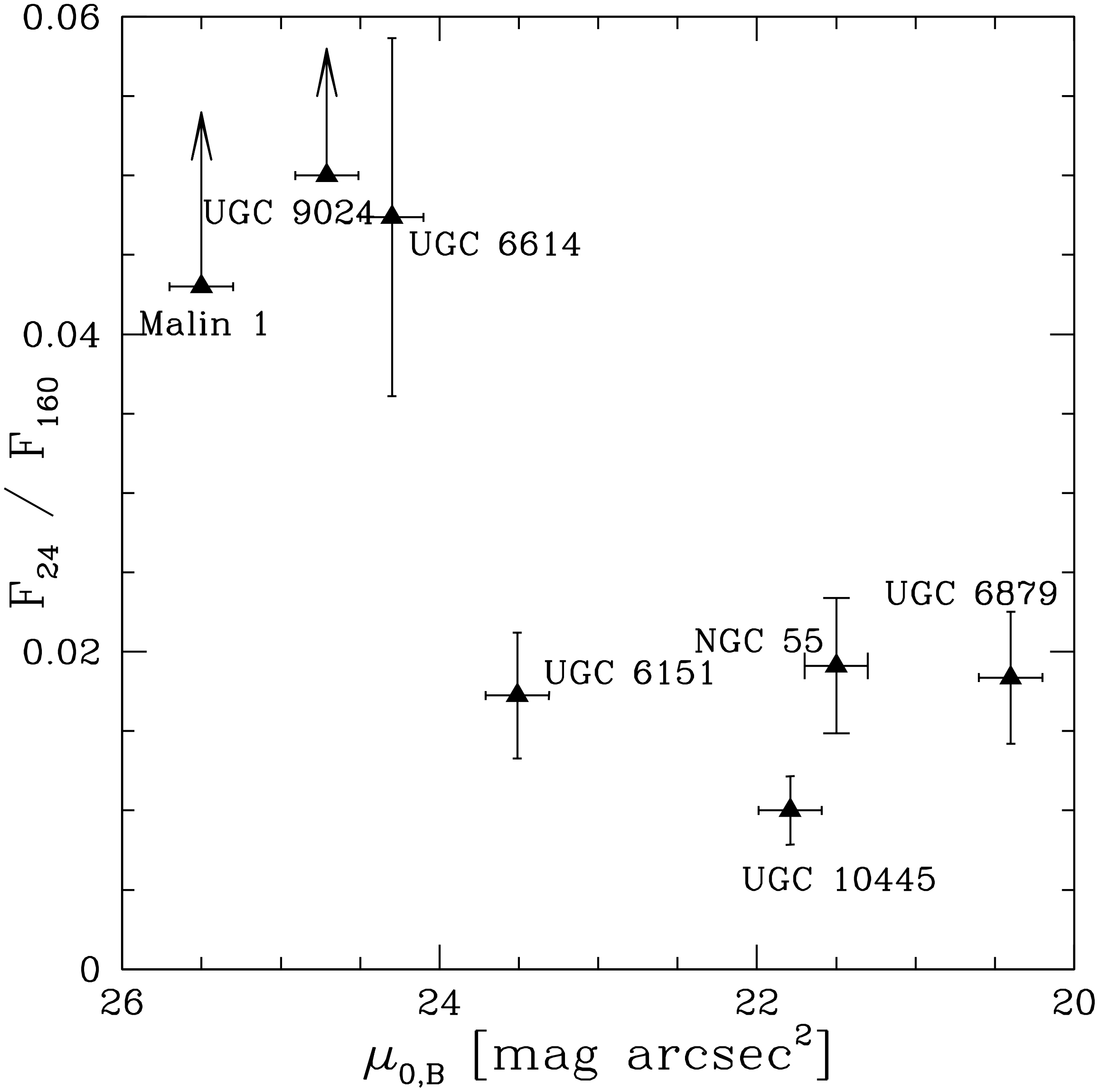

Fig. 3.— *B*-band central surface brightnesses versus the ratio of the flux densities at 24 and 160 μm for some of the galaxies that have been explored with MIPS in search of cold dust. Lower limits are given for Malin 1 and UGC 9024, which are not detected at 160 μm.

REFERENCES

Dale, D., et al. 2005, ApJ, 633, 857

Drain,, B. T., et al. 2007, ApJ, 663, 866

de Jong, R. S., et al. 2007, ApJ, 667, L49

Engelbracht, C. W., et al. 2004, APJS, 154, 248

Galliano, F., et al. 2003, A&A, 407, 159

Galliano, F., et al. 2005, A&A, 434, 867

Hinz, J. L., et al. 2006, ApJ, 651, 874

Hinz, J. L., et al. 2007, ApJ, 663, 895

Lagache, G., Abergel, A., Boulanger, F., & Puget, J.-L. 1998, A&A, 333, 709

Madden, S. C., et al. 2006, A&A446, 877

Martin, D. C., et al. 2005, ApJ, 619, L1

Misiriotis, A., et al. 2001, A&A, 372, 775

Popescu, C. C., et al. 2000, A&A, 362, 138

Popescu, C. C., et al. 2002, ApJ, 567, 221

Reach, W. T., et al. 1995, ApJ, 451, 188

Tabatabaei, F. S., et al. 2007, A&A, 466, 509

Tuffs, R. J., & Popescu, C. C. 2005, AIP Conf. Proc. 761: The Spectral Energy Distributions of Gas-Rich Galaxies, 761, 344

van Zee, L. 2000, AJ, 199, 2757

Zaritsky, D. & Christlein, D. 2007, AJ, 134, 135

This preprint was prepared with the AAS LaTeX macros v5.2.