MAPPING AND MASS MEASUREMENT OF THE COLD DUST IN NGC 205 WITH SPITZER

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ABSTRACT

We present observations at 3.6, 4.5, 5.8, 8, 24, 70 & 160μm of NGC 205, the dwarf elliptical companion of M31, obtained with the Spitzer Space Telescope. The point sources subtracted images at 8 and 24μm display a complex and fragmented infrared emission coming from both very small dust particles and larger grains. The extended dust emission is spatially concentrated in three main emission regions, seen at all wavelengths from 8 to 160μm. These regions lie approximately along NGC 205’s semi-major axis and range from ~100 to 300 pc in size. Based on our mid-to-far infrared flux density measurements alone, we derive a total dust mass estimate of the order of 3.2 × 10^4 M⊙, mainly at a temperature of ~20K. The gas mass associated with this component matches the predicted mass returned by the dying stars from the last burst of star formation in NGC 205 (~0.5 Gyr ago). Analysis of the Spitzer data combined with previous 1.1mm observations over a small central region or “Core” (18′′ diameter), suggest the presence of very cold (T~12K) dust and a dust mass about sixteen times higher than is estimated from the Spitzer measurements alone. Assuming a gas to dust mass ratio of 100, these two datasets, i.e. with and without the millimeter observations, suggest a total gas mass range of 3.2 × 10^6 to 5 × 10^6 M⊙.

Subject headings: galaxies: dwarf — galaxies: individual (NGC 205) — galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction — ISM: structure

1. INTRODUCTION

The galaxies of the Local Group, because of their proximity and our ability to carry out high spatial resolution studies in nearby systems, provide us with powerful templates to understand the chemical, morphological and kinematical characteristics, plus star formation history, of more distant galactic systems. The Local dwarf galaxies (LDGs), in particular, have been subject to numerous recent studies of their stellar populations and star formation (for summaries see for example, Hodge 1989, Mateo 1998, Grebel 2005). Dwarf ellipticals follow a different “fundamental plane” than true ellipticals (Ferguson & Binggeli 1994), nevertheless they do share many common characteristics, in particular the presence of a mostly old stellar population (Mateo 1998). One of these local dwarf systems is NGC 205, a low surface brightness dwarf elliptical companion of M31. NGC 205 is interesting because of its very conspicuous dark clouds, which were detected in some of the earliest photographic plates of M31 and its surroundings (Baade 1944; Hodge 1973)(NGC 205 lies ~ 36′ NW from the M31 nucleus). These visually dark clouds reveal the presence of an interstellar medium in a stellar population dominated by old stars, that is, in an elliptical galaxy.

There are several indicators for an intermediate and young stellar population, as well as for gas enrichment, in NGC 205. A handful of blue and UV-bright stars have been detected in its nucleus (Baade 1951; Hodge 1973; Bertola et al. 1995), with ages ranging from ~ 5 × 10^8 yr to a few 10^9 yr. In terms of metallicity, the location of its giant branch implies a mean value of [Fe/H] = −0.85±0.2 (Mould, Kristian & Da Costa 1984), higher than for most LDGs, which have values ranging from −1.1 to −2.2 (Mateo 1998). Moreover, a stellar population study of the resolved bright near-IR stars in NGC 205 (Davidge 2003) indicates that the brightest asymptotic giant branch stars formed a few tenths of a Gyr ago. All these indicators suggest an episode of star formation in NGC 205, which took place a few 10^8 years ago, and a recent replenishment of the interstellar material by this population of evolved stars. Although there is no consensus on the process which triggered such a burst, gravitational tidal interaction of NGC 205 with M31 has always been an appealing mechanism because it simultaneously explains the twisted surface brightness isophotes (Hodge 1973; Choi et al. 2002), the tidal trail of blue metal poor RGB stars (McConnachie et al. 2004; Ibata et al. 2001) and the kinematically distinct behavior and morphology of its interstellar medium, particularly of the HI gas (Young & Lo 1997).

The ISM in NGC 205 has some peculiarities. Based on the last burst of star formation ~ 5 × 10^8 yr ago (Wilcots et al. 1990; Bertola et al. 1995), one can estimate the amount gas injected back into the ISM, which is ~ 2.6 × 10^8 M⊙ (following Faber & Gallagher 1976). This mass is about three times larger than that measured by Sage, Welch & Mitchell (1998) of 7.2 × 10^7 M⊙ (from CO (H2) plus HI, scaled by a factor 1.4 to include Helium). This difference in masses led to the idea that gas is being removed by the young stars in NGC 205, either by stellar winds or supernova explosions (Welch, Sage & Mitchell 1998). Recently Haas (1998) carried out photometric observations with the Infrared Space Observatory (ISO) between 120 and 200μm that, combined
with a millimetric measurement of the central 18′′ (Fich & Hodge 1991), yielded large amounts of cold dust with mass $0.2 - 1.2 \times 10^4 M_\odot$ at $T \sim 10$ K. Assuming a gas-to-dust mass ratio of 100, the cold dust traces nearly $10^6 M_\odot$ of gas at center. There is vast observational evidence for “warm” and “cool” dust in elliptical galaxies based on mid/far infrared data (see e.g. Jura et al. 1987; Knapp et al. 1989; Ferrari et al. 2002; Temi et al. 2004; Xilouris et al. 2004). The initial IRAS measurements were limited to detection of temperatures of $\sim 30$ K traceable by the 100µm fluxes. This led to the possibility of missing a colder component with nearly 90% of the dust mass at lower temperatures ($T \sim 15 - 20$K) which is radiating at longer wavelengths (> 100µm) (see e.g. Devereux & Young 1990). The longer wavelength far infrared observations (> 100µm) combined with millimeter and sub-millimeter measurements have confirmed this picture in several early-type galaxies, where the bulk of the dust mass is cold ($\sim 20$ K) and nearly an order of magnitude larger than previously estimated (Wiklind & Henkel 1995; Temi et al. 2004).

This study presents new mid/far infrared images of NGC 205 obtained with the Spitzer Space Telescope (Spitzer). The higher sensitivity and spatial resolution enable us for the first time to look directly into the detailed structure and properties of the dust clouds in NGC 205 and to evaluate their dust properties and content. The outline of the paper is as follows. In Section 2, we describe the Spitzer observations and the data reduction. The Spitzer images are presented in Section 3, along with a description of the mid/far-IR emission morphology and a comparison with other tracers of the ISM. Additional image processing is discussed in Section 4. Dust mass measurements and gas mass estimates are derived in Section 5 using two different methods. In Section 6, we discuss the results with some of the previous mass estimates and theoretical expectations. We conclude with a summary of our findings in Section 7.

2. OBSERVATIONS

The mid-IR observations were obtained with IRAC, the infrared camera on board Spitzer (Fazio et al. 2004) on 20 January 2005 as part of the GO1 program to map M31 (PI: Barmby, Program ID: 3126). The region around NGC 205 was observed with four dithered 30 sec frames per sky position; the IRAC field of view (FOV) is 5′. The images obtained with channels 1 and 2 (at 3.6 and 4.5µm) are used mostly to determine the stellar contribution to the overall spectral energy distribution of NGC 205. The channels 3 and 4 (at 5.8 and 8µm) contain the most information about the dust properties; channel 4 in particular, with a passband centered at 7.9µm includes some of the strongest Polycyclic Aromatic Hydrocarbons (PAH) emission features known (e.g. bands at 7.7 and 8.6µm); these are considered some of the best tracers of very small particles (see e.g. Li & Draine 2001, Draine & Li 2001 and references therein). The Basic Calibrated Data produced by the SSC pipeline (Version 11) were combined with the SSC MOPEX software to produce final mosaics with pixel size 1.2″(all channels) and spatial resolutions of less than 2″ FWHM.

The far-IR data were obtained with the multiwave-photometer MIPS onboard Spitzer on 25 August 2004 (Program ID 99). These observations were taken as part of the large M31 mosaic consisting of 7 scan legs, between 0.75 and 1.25 degree long, with a 148′′ overlap between scan legs. The scanning was done at the medium scan rate covering a total area of 1° × 3° approximately oriented along the major axis of M31, with a total observing time of 17.1 hrs. The NGC 205 observations themselves have a depth of 84 sec per pixel. The

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Fig. 1.— IRAC 3.6, 4.5, 5.8 & 8µm images of NGC 205. The FOV of each image is 15′ × 15′ with N up and E to the left.

Fig. 2.— IRAC 8µm MIPS 24, 70 & 160µm images of NGC 205. The FOV of each image is 5′ × 5′ with N up and E to the left.
3. MORPHOLOGY OF INFRARED EMISSION

details of the observations and reductions are given by Gordon et al. (2006). In the three MIPS bands a background subtraction has been performed, that removes some time dependent artifacts along the scan legs. In the 70 and 160µm images some stripping remains due to a non-linear time response of the Ge:Ga arrays, however their overall effect on the flux density around NGC 205 is very small (\(\sim 1 - 2\%\)), and this is included in our uncertainties (see Section 4.1). The final 24, 70, and 160 micron images have spatial resolutions of 6, 18 and 40′′ FWHM, respectively (Rieke et al. 2004). The mosaic pixel scales are 2.49′′ at 24µm, 9.85′′ at 70µm, and 16.0′′ at 160µm.

The Spitzer data are complemented with ISOCAM observations of NGC 205 from the ISO archive. The archive data (Off Line Processing V10.0) was re-reduced using the CIA (Cam Interactive Analysis V4.0) software to improve mainly on the deglitching, following the rest of the standard reduction steps (Coulais & Abergel 2000; Blommaert et al. 2003). The data set includes images at 14.3µm covering a 204′′ × 216′′ field of view and with 6′′ per pixel. All the measurements were performed with background subtraction, and were compared with the global estimates of Xilouris et al. (2004) for consistency.

For both IRAC and MIPS we used a 15′ × 15′ section of the M31 maps centered on the position of NGC 205 [\(\alpha(2000) = 00^h 40^m 22.1^s\), \(\delta(2000) = 41° 41′ 07.1″\)]. This region is large enough to encompass most of visual size of the galaxy of 9′ × 19′ (25 B mag arcsec\(^{-2}\)) (Nilson 1973), and certainly all the mid/far IR emission (Rice et al. 1988). We adopt a distance to NGC 205 of 815 ± 35 kpc (Mateo 1998; McConnachie et al. 2004) throughout this work, i.e. at that distance, spatial structures 1″ across measure \(\sim 3.9\) pc. This tentatively puts NGC 205 behind M31, which is at a distance of 780 kpc (Rich et al. 2005; McConnachie et al. 2005).

Figure 1 and 2 show the images of NGC 205 taken with IRAC at 3.6 & 4.5µm (stellar emission dominant, see Table 4) and at 5.8, 8, 24, 70 & 160µm (dust emission dominant, see Table 4). Figure 3 displays a three color image of NGC 205 where the dust clouds at 5.8 and 8µm stand out within the stellar background detected by the shorter wavelength bands. The higher angular resolution images at 8 and 24µm display a spatially complex and fragmented extended emission. We expect that the main contribution to the 8µm emission arises from aromatic molecules and at 24µm from submicron-sized grains (Li & Draine 2001; Xilouris et al. 2004). The overlay of these two wavelengths (Fig. 4) shows the close spatial relationship between these two dust distributions. However, the 8µm image shows more extended emission than at 24µm (see Fig. 5).

The morphology of the diffuse emission is complex and clumpy; nevertheless we can clearly identify three spatially distinct emission regions: the largest region to the south with a size of \(\sim 76′′ × 37′′\) (\(\sim 300\) pc × 146 pc), the central region with a size of \(\sim 49′′ × 28′′\) (\(\sim 193\) pc × 110 pc), and the smallest region to the north with a size \(\sim 33′′ × 31′′\) (\(\sim 130\) pc × 123 pc) (see Fig. 4 and Table 1). Even at the lower resolution of the 70 and 160µm bands (see Fig. 2), where the bulk of the emission is produced by dust emission from the larger grains (\(\sim 0.1-0.5\mu m\)), Desert, Boulanger & Puget 1990; Li & Draine 2001), one can easily identify the same three large regions seen at shorter wavelengths. We have included also a “Core” region with a diameter of 18.′4 for which 1.1mm observations are available (Fich & Hodge 1991).

The 14.3µm ISOCAM observations, however, cover a smaller FOV and the final mosaic has some vignetting that leaves an effective FOV of \(\sim 192′\) radius. Although our mosaic is a bit larger than that presented by Xilouris et al. 2004 (Fig. A.1), the “South” and “Total” regions are 3% and 6% smaller at 14.3µm, respectively, than at all other wavelengths (see Table 3). Therefore, the emis-
TABLE 1
NGC 205 Emission Regions

| Region | RA (J2000) | Dec (J2000) | Area |
|--------|------------|-------------|------|
|        | h m s      | o r. s      |      |
| North  | 0 40 24.00 | 41 41 49.9  | 0.24 |
| Center | 0 40 22.29 | 41 41 09.4  | 0.30 |
| South  | 0 40 23.75 | 41 40 10.3  | 0.55 |
| Core   | 0 40 22.29 | 41 41 09.4  | 0.07 |
| Total  | 0 40 22.38 | 41 40 52.3  | 4.36 |

*elliptical aperture as shown in Fig. 4

Fig. 5.— IRAC 8 μm grayscale image of NGC 205 where point sources have been removed to reveal more clearly the extended diffuse emission. The image is displayed at high contrast to enhance the faint emission surrounding the bright central region. The FOV is 15′ × 15′ with N up and E to the left.

A comparison of the mid/far IR data with other tracers of the ISM, such as HI (Young & Lo 1997), shows the same morphology (see Fig. 6), indicating that dust and gas are very well mixed in NGC 205. Based on the HI velocity data, it is clear that the HI gas rotates in the North-South direction with a velocity gradient of 42 km s\(^{-1}\) over 900 pc (Young & Lo 1997). However, there is no clear one-to-one correspondence between the HI column density peaks and velocity, and therefore, the three distinct IR emission regions are not necessarily dynamical entities. The observed dust morphology is similar at all wavelengths from 8 to 160 μm (within the limits of varying angular resolution) and also similar to the HI morphology seen in the 21-cm line. The data is consistent with an ISM in which the atomic gas and dust are very well mixed in NGC 205. Based on the results shown at the bottom of Figure 7, we estimate that about half of the point sources in the central region of NGC 205 are from foreground contamination due to their much “bluer” [8]-[24] color and, consequently, we conclude that none are present in the central region of NGC 205.

The foreground contamination at 24 μm, from M31 point sources, where dusty AGBs contribute most of their flux, is estimated using six control fields. Each field has dimension 15′ × 15′ to match that of NGC 205 and is located a comparable distance away from the center of M31 (Table 2). To determine the number of AGB stars in NGC 205, we count these stars in the central 15′ square region and estimate the number of foreground stars by averaging their numbers in the six control fields. Based on the results shown at the bottom of Figure 7, we estimate that about half of the point sources in the NGC 205 15′ × 15′ field are from foreground contamination due to the MW or M31.

We estimate that in the smaller “Total” region centered on NGC 205 (as defined in Table 1), about a third of the point sources are from foreground contamination. Given a mean flux density of 0.6 mJy for contaminating point sources (see Fig. 7, bottom), we estimate a flux density contamination of ∼ 2 mJy. This number is be-
low our flux density measurement errors at 24\,\mu m (see Table 3) and therefore no further processing, i.e. point source removal, is done to the 24\,\mu m image.

### Table 2

| Field       | RA (J2000) | Dec (J2000) |
|-------------|------------|-------------|
| NGC 205     | 0 40 22.10 | 41 41 07.1  |
| control field a | 0 36 38.65 | 40 37 47.0  |
| control field b | 0 44 54.11 | 40 51 03.5  |
| control field c | 0 43 36.11 | 40 31 49.4  |
| control field d | 0 46 24.97 | 41 10 13.8  |
| control field e | 0 47 38.73 | 41 28 52.5  |
| control field f | 0 42 54.21 | 42 19 51.6  |

#### 4.1. Aperture Correction of Extended Sources

We measure the IRAC 3.6, 4.5, 5.8, & 8\,\mu m and the MIPS 24, 70, & 160\,\mu m fluxes in the spatially resolved regions common at all wavelengths, as depicted in Figure 4 and listed in Table 1. The IRAC and MIPS data are combined with previous observations taken with ISO at 14.3\,\mu m (Xilouris et al. 2004) and JCMT at 1.1\,mm (Fich & Hodge 1991). The flux uncertainty for each region includes the combined effect of the systematic errors due to the post processing of the images, plus that of the flux density calibration of the instruments (Fazio et al. 2004; Rieke et al. 2004). The flux uncertainty, therefore, was estimated by measuring the residual flux density away from the galaxy in the background subtracted images and adding an absolute flux calibration uncertainty of 10\% for the IRAC and MIPS 24\,\mu m measurements, and of 20\% for the ISO 14.3\,\mu m and MIPS 70 & 160\,\mu m fluxes. The 8\,\mu m fluxes are corrected (multiplied) by the effective aperture correction factor of 0.944 (3.6\,\mu m), 0.772 (5.8\,\mu m), and 0.737 (8\,\mu m) (Reach et al. 2005). The corrected flux densities and uncertainties are given in Table 3.

#### 4.2. Stellar Photospheric Component of Diffuse Emission

The stellar photospheric component of the diffuse emission coming from NGC 205 itself must be removed before the analysis of the dust component. We conservatively assume that, in addition to the 2MASS J, H, and K bands, all the light in the 3.6 and 4.5 IRAC bands is photospheric in origin. The J, H, K, IRAC 3.6 and 4.5 filter response functions were multiplied with a PEGASE stellar model (Fioc & Rocca-Volmerange 1997) with an age of 350 Myr (see Fig. 9) and integrated over wavelength yielding fluxes that can be compared with the observed fluxes. The age was picked to roughly coincide with the (uncertain) epoch of recent star formation in NGC 205 (see eg. Butler & Martinez-Delgado 2005; Davidge 2005). There is no diagnostic power in the age assumed; we used synthetic spectra from Simple Stellar Population (SSP) models only to estimate the stellar contribution to the Spitzer bands, as simple power laws cannot reproduce the J, H, K colors. Scalings were derived for each band individually and averaged together to get the final scaling for the photospheric component. In all cases, the J through 4.5\,\mu m fluxes are consistent with being completely stellar.
in origin. To estimate the photospheric contribution to the flux density at longer wavelengths, we multiplied and integrated over wavelength the relevant IRAC and MIPS bandpasses with the PEGASE model and subtracted the result from the observed flux density to yield an estimate for the total dust flux density. For the relative contributions of the diffuse photospheric emission to the observed fluxes, see Table 4. The age we use for the PEGASE models (within a factor of 3) does not significantly alter the dust fits; indeed, PEGASE models between 0.1−1 Gyr result in very similar estimates for the stellar contamination in the Spitzer bands, especially for λ ≥ 8 μm.

### Table 4

**Stellar Photospheric and Dust Flux Density Contributions**

| Region  | Wavelength (μm) | Total* Flux Density (mJy) | Dust Flux Density (mJy) | Stellar* Dust Fraction |
|---------|------------------|---------------------------|------------------------|------------------------|
| North   | 3.6              | 20.8                      | 0.0                    | 1.0                    | 0.00 |
|         | 4.5              | 12.6                      | 0.0                    | 0.60                   | 0.00 |
|         | 5.8              | 15.2                      | 6.4                    | 0.42                   | 0.42 |
|         | 8.0              | 11.7                      | 6.6                    | 0.25                   | 0.56 |
|         | 14.3             | 6.9                       | 5.2                    | 0.08                   | 0.75 |
|         | 24.0             | 10.1                      | 9.5                    | 0.03                   | 0.94 |
|         | 70.0             | 104.2                     | 104.2                  | 0.00                   | 1.00 |
|         | 160.0            | 472.9                     | 472.9                  | 0.00                   | 1.00 |
| Center  | 3.6              | 58.6                      | 0.0                    | 1.0                    | 0.00 |
|         | 4.5              | 35.4                      | 0.0                    | 0.60                   | 0.00 |
|         | 5.8              | 32.6                      | 7.2                    | 0.43                   | 0.22 |
|         | 8.0              | 25.5                      | 10.7                   | 0.25                   | 0.42 |
|         | 14.3             | 14.9                      | 9.8                    | 0.08                   | 0.66 |
|         | 24.0             | 17.6                      | 15.7                   | 0.03                   | 0.89 |
|         | 70.0             | 181.5                     | 181.5                  | 0.00                   | 1.00 |
|         | 160.0            | 712.9                     | 712.9                  | 0.00                   | 1.00 |
| South   | 3.6              | 54.1                      | 0.0                    | 1.0                    | 0.00 |
|         | 4.5              | 32.8                      | 0.0                    | 0.60                   | 0.00 |
|         | 5.8              | 38.8                      | 15.5                   | 0.40                   | 0.40 |
|         | 8.0              | 25.7                      | 12.1                   | 0.23                   | 0.47 |
|         | 14.3             | 25.5                      | 20.9                   | 0.09                   | 0.82 |
|         | 24.0             | 25.8                      | 24.0                   | 0.03                   | 0.93 |
|         | 70.0             | 300.8                     | 300.8                  | 0.00                   | 1.00 |
|         | 160.0            | 1490.0                    | 1490.0                 | 0.00                   | 1.00 |
| Total   | 3.6              | 437.6                     | 0.0                    | 1.0                    | 0.00 |
|         | 4.5              | 265.7                     | 0.0                    | 0.61                   | 0.00 |
|         | 5.8              | 279.0                     | 89.3                   | 0.43                   | 0.32 |
|         | 8.0              | 147.9                     | 37.6                   | 0.25                   | 0.25 |
|         | 14.3             | 101.4                     | 63.9                   | 0.09                   | 0.63 |
|         | 24.0             | 141.4                     | 127.2                  | 0.03                   | 0.90 |
|         | 70.0             | 1428.0                    | 1428.0                 | 0.00                   | 1.00 |
|         | 160.0            | 8761.3                    | 8761.3                 | 0.00                   | 1.00 |
| Core    | 3.6              | 23.1                      | 0.0                    | 1.0                    | 0.00 |
|         | 4.5              | 14.9                      | 0.0                    | 0.64                   | 0.00 |
|         | 5.8              | 14.2                      | 5.1                    | 0.40                   | 0.36 |
|         | 8.0              | 14.5                      | 9.3                    | 0.22                   | 0.64 |
|         | 14.3             | 5.9                       | 4.1                    | 0.08                   | 0.69 |
|         | 24.0             | 5.1                       | 4.4                    | 0.03                   | 0.87 |
|         | 70.0             | 61.7                      | 61.7                   | 0.00                   | 1.00 |
|         | 160.0            | 253.2                     | 253.2                  | 0.00                   | 1.00 |
|         | 1100.0           | 21.0                      | 21.0                   | 0.00                   | 1.00 |

*The measured flux density (photospheric plus dust contributions)

Stellar flux density normalized with respect to that at 3.6 μm.

5. **MASS OF DUST AND GAS IN NGC 205**

With these new *Spitzer* observations, it is possible to derive the mass of dust and estimate the gas mass in NGC 205 using different methods and compare the results, for the total emission as well as within the three main emission regions.

In the first method, we use a single-temperature fit to the 70 and 160 μm data to determine the dust temperature, assuming a modified blackbody emissivity function of the form:

\[
F(\lambda) = \lambda^{-\beta} \frac{2hc^2\lambda^{-5}}{e^{hc/\kappa_\lambda T} - 1}
\]  

We adopt an emissivity coefficient β = 2 (valid beyond 70 μm; cf. Draine 2003). Assuming a gas-to-dust mass ratio of ~100, representative of the solar neighborhood and the inner disk of the Milky Way (Hildebrand 1983; Devereux & Young 1990), the dust temperature and emissivity can be used to estimate the mass of dust and gas. This method has been extensively used to determine dust masses in galaxies, but it has a few drawbacks (Devereux & Young 1989; Dale & Helou 2002) and should be taken as an approximation. A fit to the spectral energy distribution (SED) has been shown to provide better estimates to the dust masses for each dust grain component (see below).

A reliable ratio of the far-IR fluxes is a necessary ingredient to get the best temperature estimate. The angular resolution of the 70 μm image was reduced to match that at 160 μm by convolving the image with the 160 μm kernel, derived from the PSF model generated using the TinyTim software (Krist 2002). The IRAF routines `geomap` and `geotran` were then used to match the pixel scale and astrometry, preserving the flux in the transformation. Each pixel is assigned a temperature based on the best fit to the modified blackbody function. The resulting temperature map is shown in Figure 8. The temperature is very uniform, ranging from ~14−17 K in the innermost 5′ that encompasses the three main emission regions. In the central rectangular region of size 2.1′×2.9′ (or an area of 6.3′×2), slightly larger than the “Total” region as defined in Table 1, we calculate the dust mass from the 160 μm emission using the following equation:

\[
M_d = S_\nu D^2/\kappa_\nu B_\nu T
\]  

where D is the distance to the galaxy of 815 kpc and κd is the mass absorption coefficient for which we assume a value of 6.73 m² kg⁻¹ at 70 μm and 1.2 m² kg⁻¹ at 160 μm (Li & Draine 2001). The total dust mass in this region, derived from the sum of the individual mass estimate for each pixel, is 6.1 ± 1.2 × 10⁴ M⊙, yielding a gas mass of 6.1 × 10⁶ M⊙ for a gas-to-dust mass ratio of 100.

Alternatively, we can determine dust masses by fitting the total dust emission SED. The SED was measured between 5.8 and 160 μm, using IRAC, ISO 14.3 μm and MIPS data. We measure the fluxes in the spatially resolved regions common to all wavelengths, as depicted in Figure 4 and listed in Table 3.

The dust emission in NGC 205 was modeled by an equation of the form:

\[
F_{\text{dust}}(\lambda) = \sum C_i \kappa_i(\lambda) B_\lambda(T_{D,i})
\]

where the sum extends over i dust components, C_i = M_{d,i}/D^2, D as in Eq. 2, and κ_i is the mass absorption coefficient of the i-th dust component. For NGC 205,
the relatively large 5.8, 8, and 14.3\(\mu\)m fluxes require a hot component which we ascribe to PAH molecules. While the 70 and 160\(\mu\)m emission could be fit with a single temperature component, including the 24\(\mu\)m and 1.1\(\mu\)m fluxes requires additional temperature components. To satisfactorily fit the full SED of NGC 205, we adopt a 3 component model: warm and cold silicates (\(a \sim 0.1\mu\)m) and PAHs, the former to reproduce the 24-1100\(\mu\)m emission and the latter, the 5.8-24\(\mu\)m emission. Mass absorption coefficients for astronomical silicates were computed from Mie theory using the dielectric functions of Laor & Draine (1993). Cross sections for the PAH molecules were taken from Li & Draine (2001). As the canonical PAH spectrum (e.g. NGC 7027, Werner et al. 2004) exhibits no features beyond 20\(\mu\)m, we re-computed the PAH cross-sections (and mass absorption coefficients) leaving off the last three terms of Li & Draine’s Eq. 11. The PAH component is included here for completeness of the fit, but we do not use the temperature or mass estimates as the PAH emission is a stochastic process rather than an equilibrium process as assumed in Eq. 3.

With only 6 measurements and 6 parameters \((C_{1,2,3,TD_{1,2,3}})\), a formal fit is not fully constrained and we proceed by making a detailed search of parameter space. With our assumptions about the components present in the observed SED, we searched a limited set of parameters for dust mass (through \(C_i\)) and temperature for each component. We assumed temperature ranges of 200-550 K, 25-150 K, and 8-25 K for the PAH, warm, and cold silicates, respectively. At each set of temperature points, a similar grid of mass scalings \((C_i)\) was explored for each component. After an initial, coarse grid search, a finer temperature and mass scaling grid was defined for each component and the procedure repeated. We iterate this procedure (typically only two refinements of the grid were needed) until a good fit in the \(\chi^2\) sense was found.

We estimated uncertainties in the derived quantities by examining the distribution of \(\chi^2\) about the minimum for all input parameter sets (typically 1 \(\times\) 10\(^3\) - 1 \(\times\) 10\(^6\) points in the six dimensional parameter space). While the results of this procedure are not unique, it yields representative estimates of both the dust mass and temperature, given the input assumptions. In all cases the dust mass is dominated by the cold component and should be considered as a weak lower limit. Owing to the lack of data beyond 160\(\mu\)m, we cannot formally rule out much larger dust masses. However, several pieces of evidence argue against dust masses at the upper end of the formal error bars. First, where we do have sub-mm data (“Core” region), the dust mass is consistent with much lower upper “limits” on the mass and second, the upper error limits would imply very large fluxes at sub-mm wavelengths, which is not what is observed (Fich & Hodge 1991).

The best SED fits to the data for each region, which produce the dust masses and temperatures given in Table 5, are shown in Figure 9 and 10. Using the same gas-to-dust mass ratio of 100, we infer a gas mass for the “Total” region of 3.2 \(\times\) 10\(^6\)\(M_\odot\). This value is nearly one half of the 6.1 \(\times\) 10\(^6\)\(M_\odot\) mass derived from the 70 to 160\(\mu\)m flux ratio method. Summing up the total dust mass in the three distinct large regions using the best fit values, we estimate a gas mass of 1.7 \(\times\) 10\(^6\)\(M_\odot\), i.e. smaller than that of the “Total” region. This result suggests that a larger reservoir of gas/dust with a comparable gas mass surrounds the three regions, as first suggested by the HI (Young & Lo 1997) and CO (Welch, Sage & Mitchell 1998) observations.

The “Core” region has a detection at 1.1\(\mu\)m (Fich & South 5, 53\(^\circ\) North 1, 58\(^\circ\)). The “Core” region and temperature estimates as the PAH emission is a stochastic process rather than an equilibrium process as assumed in Eq. 3.

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| Cloud | Warm Silicates | Cold Silicates |
|-------|----------------|---------------|
| North | 1.2\(^+\)\(^3\)\(M_\odot\) | 2.2\(^+\)\(^8\) \(\times\) 10\(^4\)\(M_\odot\) |
|       | 53\(^+\)\(^8\) K    | 17.5\(^+\)\(^8\) K  |
| Center| 2.1\(^+\)\(^3\)\(M_\odot\) | 2.9\(^+\)\(^8\) \(\times\) 10\(^4\)\(M_\odot\) |
|       | 53\(^+\)\(^11\) K    | 17\(^+\)\(^8\) K    |
| South | 5.3\(^+\)\(^3\)\(M_\odot\) | 1.2\(^+\)\(^8\) \(\times\) 10\(^4\)\(M_\odot\) |
|       | 51\(^+\)\(^18\) K    | 15.8\(^+\)\(^8\) K  |

\(^a\)SED without the 1.1\(\mu\)m flux density measurement
\(^b\)SED includes the 1.1\(\mu\)m flux density measurement

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The “Core” region has a detection at 1.1\(\mu\)m (Fich & Hodge 1991), and adding this value to its SED and computing a new fit, results in a dust mass of 1.8 \(\times\) 10\(^4\)\(M_\odot\), i.e. approximately a factor of sixteen larger than the mass estimated without the 1.1\(\mu\)m point (1.1 \(\times\) 10\(^3\)\(M_\odot\)), and at a colder temperature, 11.6 K (compared to 17.8 K). One can speculate that if this colder dust component has a similar distribution across our selected regions, preserving the same mass gas-to-dust ratio, then one predicts a gas mass several times larger, \(\sim 5 \times 10^7\)\(M_\odot\). This mass determination is consistent with the fact that adding submillimeter measurements to far-IR observations of early-type galaxies usually yields larger cold dust mass esti-
FIG. 9a.— Infrared SEDs of the “North” (top left) and “Center” (top right) region of NGC 205 (see Table 1). The diagrams show the SED fit to the IRAC, 14.3µm ISO, and MIPS measurements (Table 3). The solid points are the data (stellar photospheric component removed) and the open points are the model multiplied with the passband and integrated over wavelength. The dotted line is the PAHs component, the dashed line is the warm silicates component, the dot-dashed line is the cold silicates component and the solid line is the total of all components.

FIG. 9b.— Infrared SEDs of the “South” (bottom left) and “Total” (bottom right) region of NGC 205 (see Table 1).

cent mass dust determination in the same region by Haas (1998), adding ISO data between 120 and 200µm to the SED, is $M_{\text{dust}} = 0.88 \times 10^3 M_\odot$ without the 1.1mm data and $M_{\text{dust}} = 1.18 \times 10^3 M_\odot$ including it (for a emissivity exponent $\beta = 2$), i.e. a factor of four higher than Fich & Hodge’s upper limit. Using the Spitzer data alone, we estimate for the “Core” region $M_{\text{dust}} = 1.1 \times 10^3 M_\odot$. If we include the 1.1mm data, the mass estimate increases to $M_{\text{dust}} = 1.8 \times 10^3 M_\odot$. This latter value is similar to that obtained by Haas, except that our dust temperature is 11.6 K rather than 8 K. Therefore the mass of gas, for a gas-to-dust ratio of 100, for NGC 205 “Core” region is $M_{\text{gas}} = 1.8 \times 10^6 M_\odot$. Using only our FIR Spitzer data for the SED, we determine a “Total” amount of dust at 18 K of $M_{\text{dust}} = 3.2 \times 10^4 M_\odot$, which implies a mass of gas, $M_{\text{gas}} = 3.2 \times 10^6 M_\odot$. This latter value is four times larger than ISM mass determination of $M_{\text{ISM}} = 7.2 \times 10^5 M_\odot$ by Sage, Welch & Mitchell (1998), and in perfect agreement with the theoretical gas mass estimate of $M_{\text{gas}} = 2.6 \times 10^6 M_\odot$, generated by the injection of gas by evolved stars over 0.5 Gyr. This comparison suggests that the mass deter-

6. DISCUSSION

One of the open issues in understanding the ISM of NGC 205 has been its “missing ISM mass”, i.e. the apparent lack of gas in comparison with the expected mass return to the interstellar medium by evolved stars (Welch, Sage & Mitchell 1998). By determining the dust mass and selecting a reasonable gas-to-dust mass ratio (e.g. 100), one can estimate the amount of gas in a straightforward manner.

The dust mass estimate for the “Core” of NGC 205 from Fich & Hodge (1991) using IRAS data and including 1.1mm observations is $M_{\text{dust}} = 1 - 3 \times 10^3 M_\odot$, depending on the adopted value for the dust emissivity. The re-
New IRAC and MIPS observations of NGC 205 give a better assessment of the total dust mass in this prototypical LDG system. The Spitzer data have been complemented with ISO Cam archival data to create a well defined spectral energy distribution in the 3.6 to 160µm wavelength range. The higher sensitivity and angular resolution of IRAC and MIPS provide a detailed view of the morphology of the interstellar medium in NGC 205. At 8 and 24µm the spatial structure of the warm dust is clearly resolved. Although the 8 and 24µm images resemble the drawings of the dust clouds inferred by Hodge (1973) using isodensity measurements of the ground based visual photographic plates (c.f. Welch, Sage & Mitchell 1998, Fig. 1; Young 2000, Fig. 1), these new IR data display a more complex structure. To facilitate our analysis of the color temperature and dust masses, we identified three main regions. As shown in Figure 2, the dust clouds within these regions are bright and conspicuous at the longer wavelength too, having sizes ranging from ~100 to 300 pc, and dust masses of ~10^3−10^4 M⊙. A larger “Total” area encompasses the three regions, and covers most of the bright 160µm dust emission.

The derived dust masses, based on the 70 to 160µm flux ratio and a best fit to the SED, imply gas masses (assuming a standard gas-to-dust mass ratio of 100 (cf Young 2000)), that are consistent with other and larger (3.2−6.1×10^6 M⊙) than previously estimated from CO and HI observations. This indicates that a significant contribution to the dust and gas masses is coming from a fainter component surrounding the brightest emission regions. Adding the 1.1mm detection to our measurements of the “Core” region of NGC 205, increases by a factor of sixteen the estimate of the cold dust in that region. Our gas mass estimate in NGC 205 is a factor of four larger than previously detected, but it could be still larger if the distribution of the very cold dust (~12−14 K) spreads out to the three selected regions. If this is the case, the gas mass would be sixteen times the “Total” (Table 5), i.e. 5×10^7 M⊙ for a gas-to-dust mass ratio of 100. Overall the gas estimates are therefore consistent with the predicted mass return from dying stars, based on the last burst of star formation, 5×10^8 yr ago.

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