We present Herschel SPIRE and PACS photometric observations of the low metallicity (Z ~ 0.35 Z_⊙) nearby dwarf galaxy, NGC 1705, in six wavelength bands as part of the Dwarf Galaxy Survey guaranteed time Herschel key program. We confirm the presence of two dominant circumnuclear IR-bright regions surrounding the central super star cluster that had been previously noted at mid-IR wavelengths and in the sub-mm by LABOCA. On constructing a global spectral energy distribution using the SPIRE and PACS photometry, in conjunction with archival IR measurements, we note the presence of an excess at sub-mm wavelengths. This excess suggests the presence of a significant cold dust component circumnuclear IR-bright regions surrounding the central super star cluster that had been previously noted at mid-IR wavelengths and in the sub-mm. Although alternative explanations for the sub-mm excess beyond 350 μm, such as changes to the dust emissivity cannot be ruled out, the most likely explanation for the observed submillimetre excess is that of an additional cold dust component.

Key words. galaxies: dwarf – dust, extinction – evolution

1. Introduction

Understanding the origin and evolution of dwarf galaxies is important in modern observational cosmology. Current models for galaxy formation fall into two distinct categories: construction from the “top-down” or from the “bottom-up”. Which scenario is correct? Unfortunately, the answer is still somewhat ambiguous and left open to interpretation as both models face critical problems, in particular due to a lack of detailed, high resolution studies at redshifts corresponding to the peak era of galaxy formation. Bottom-up models over-predict the number and the mass spectrum of satellites seen around galaxies such as our own and there are inconsistencies with the timescale of the build up of larger galaxies (e.g., Prantzos & Silk 1998). A major source of this ambiguity may arise from the fact that accurate measurements of the interstellar medium (ISM) properties and star formation histories of dwarf galaxies have been lacking for the most part. To address this crucial issue, we have begun to focus our study of galaxy evolution onto analogues of these earliest galaxy building blocks right on our door step – nearby, low metallicity dwarf galaxies – where we can begin to discern the evolutionary processes at work in these objects under these very special conditions. Such objects are the most common type of galaxy in the current epoch, making up 95% of the Local Group galaxies alone (Mateo 1998).

As part of this effort to understand the nature of the evolution of dwarf galaxies, we present Herschel photometric observation of the nearby (5.1 ± 0.6 Mpc, Tosi et al. 2001) dwarf starburst galaxy, NGC 1705. The galaxy is dominated optically by a massive central super star cluster (SSC) NGC 1705-1 (Meurer et al. 1995), whilst studies in the mid and far-IR (Cannon et al. 2006; Galametz et al. 2009) reveal the presence of two bright infrared regions flanking the central SSC, offset by ~250 pc from the SSC, with these off-nuclear regions dominating the global IR emission of NGC 1705. This galaxy provides an ideal environment for exploring the effects of ongoing, massive star formation on the environment within a dwarf galaxy (Cannon et al. 2006), given its sub-solar nebular metallicity (Z ~ 35% Z_⊙; Lee et al. 2004; and large reservoir of gas, Meurer et al. 1998), as we can trace the effects of the SSC on the surrounding interstellar medium, and in particular, can characterize the nature of dust and PAH emission.

2. Observations

NGC 1705 was observed as part of the Dwarf Galaxy Survey programme (P. S. Madden), a guaranteed time (GT) key program with the objective of mapping the dust and gas in 51 nearby dwarf galaxies: dwarf – dust, extinction – evolution.

(Affiliations are available in the online edition)

Received 30 March 2010 / Accepted 11 May 2010

ABSTRACT

We present Herschel photometric observations of the low metallicity (Z ~ 0.35 Z_⊙) nearby dwarf galaxy, NGC 1705, in six wavelength bands as part of the Dwarf Galaxy Survey guaranteed time Herschel key program. We confirm the presence of two dominant circumnuclear IR-bright regions surrounding the central super star cluster that had been previously noted at mid-IR wavelengths and in the sub-mm by LABOCA. On constructing a global spectral energy distribution using the SPIRE and PACS photometry, in conjunction with archival IR measurements, we note the presence of an excess at sub-mm wavelengths. This excess suggests the presence of a significant cold dust component circumnuclear IR-bright regions surrounding the central super star cluster that had been previously noted at mid-IR wavelengths and in the sub-mm. Although alternative explanations for the sub-mm excess beyond 350 μm, such as changes to the dust emissivity cannot be ruled out, the most likely explanation for the observed submillimetre excess is that of an additional cold dust component.
dwarf galaxies, sampling a broad metallicity range of 1/50 to 1/3 \( Z_\odot \).

2.1. SPIRE observations and data processing

The galaxy was observed by SPIRE (Griffin et al. 2010) at 250, 350 and 500 \( \mu m \) in scan-map mode with scanning rate 30"/s, with the final map covering roughly 16 x 16 arcmin. The measured 1\textsigma noise level are 5-7 mJy beam\(^{-1}\) at 250, 350 and 500 \( \mu m \) respectively; the noise levels in the images are dominated by confusion. The data were processed using the HIPE pipeline (see Pohlen et al. 2010, for a detailed description; Swinyard et al. 2010; for calibration accuracy and Bendo et al. 2010b, for details on the destripper). The pipeline produces maps with a pixel size of 6.0, 10.0 and 14.0" at 250, 350 and 500 \( \mu m \) respectively. The ICC has released some interim small correction factors to improve the preliminary calibration. All flux values derived using the current standard calibration file for the flux conversion, are multiplied by 1.02, 1.05, and 0.94, for the 250 \( \mu m \), 350 \( \mu m \), and 500 \( \mu m \) maps, giving final global fluxes of 0.85 \( \pm \) 0.13, 0.38 \( \pm \) 0.06 and 0.26 \( \pm \) 0.04, respectively, using an aperture of 72" as per Galametz et al. (2009). The uncertainty in the flux calibration is of the order of 15%.

2.2. PACS data processing

The galaxy was observed by PACS (Poglitsch et al. 2010) at 70, 100 and 160 \( \mu m \) in scan map mode for a total of 1504 s, with the final map covering roughly 7 x 6 arcmin. The PACS data were reduced starting from the Level 0 product using the HIPE version 3.0 data reduction software and the HIPE responsivity calibration file version 1, corrected by factors provided by the ICC. We applied the basic steps of the standard reduction pipeline to perform the data reduction to the Level 1, where we mask the bad and saturated pixels, apply a flat field correction and perform a multi-resolution median transform (MMT) deglitching and apply a second order deglitching procedure to the data. We mask the data contributing to the bright structures in the data cube and perform polynomial fits on half scan legs to subtract the baselines. This process removes most of the drifts of the maps. Two dimensional maps are finally constructed using the MadMap procedure of HIPE. Striping is visible in a single scan but is mostly removed by the cross scan. The pipeline produces maps with a pixel size of 3.2, 3.2 and 6.4" at 70, 100 and 160 \( \mu m \) respectively. In this version of the responsibility calibration file, an error still exists in the flux scale. The final reduced global fluxes have to be scaled down by 1.05, 1.09 and 1.29 for the blue (PACS 70), green (PACS 100) and red (PACS 160) bands, giving 1.05 \( \pm \) 0.12, 1.22 \( \pm \) 0.13 and 1.18 \( \pm \) 0.12 Jy, respectively, using an aperture of 72" as per Galametz et al. (2009). The uncertainty in the flux calibration is of the order of 10%.

3. Results and discussion

3.1. Morphology of NGC 1705

The reduced SPIRE and PACS maps of NGC 1705 are presented in Fig. 1. To perform aperture photometry on individual sources with NGC 1705 for both the SPIRE and PACS images, we used the IRAF package apphot, in which the background is estimated using annuli just outside the boundaries of our galaxy. To determine the flux densities at MIPS bands, as a comparison to the PACS fluxes, the observations are convolved and re-gridded to a common resolution (FWHM MIPS 160 \( \mu m \): 40\textprime\prime). We use convolution kernels (Gordon et al. 2008; Bendo et al. 2010a,b) which convert a higher resolution PACS point-spread function (PSF) to lower resolution MIPS PSFs using Fourier transforms.

As can be seen in both sets of images, the morphology of NGC 1705 is quite complex – the far-IR emission is dominated by the off-center sources previously noted by Cannon et al. (2006) and Galametz et al. (2009). As might be expected, the two IR regions are clearly resolved at the shortest PACS wavelengths, with no emission detected from the central SSC which indicates very little in the way of significant dust emission within the central SSC itself. As we move into the SPIRE bands (beyond 250 \( \mu m \)), the individual components are no longer resolved. As noted in Galametz et al. (2009), the off-center bright IR fluxes do not have stellar counterparts. There is no indication of the presence of the offset peak to the west of the galaxy in the PACS or SPIRE that had been previously noted by Galametz et al. (2009), nor are there counterparts to the faint 24 \( \mu m \) sources.
also noted. Of note is the fact that the easternmost IR source (D1, in the nomenclature of Cannon et al. 2006) is the brightest among the different resolved wavelength maps, and is of the order of 1.15–1.45 times brighter than the western source, with the flux ratio peaking at 100 μm – previous IRS spectroscopy by Cannon et al. (2006) confirms the strongest PAH emission in this region, which in conjunction with the Herschel data is suggestive of a greater concentration/contribution to the dust mass within this region versus both the westernmost region and the SSC.

3.2. Spectral energy distribution of NGC 1705

3.2.1. Cold dust component scenario

To quantify the contributions to the IR luminosity from various dust populations within NGC 1705, we attempted to fit modified blackbody functions to the SPIRE and PACS measurements in an attempt to obtain dust component luminosities, masses and dust temperatures. On fitting, it became quickly apparent that fitting a single blackbody to the SPIRE and PACS fluxes was not possible, as the SED diverged from a single temperature fit longward of approximately 350 μm with the 350 and 500 μm fluxes higher than the fit, a trend that was confirmed with the addition of the LABOCA 850 μm flux from Galametz et al. (2009). Even the addition of a second modified blackbody function to the fit was unable to fit to a reasonable degree the 350 and 500 μm fluxes in conjunction with the LABOCA flux – we tried to fit a number of modified blackbodies with a range of realistic emissivity values between 1 and 2, and were unable to obtain a satisfactory fit that suitably fit the three longest wavelength fluxes.

In light of this, we instead constructed a global spectral energy distribution for NGC 1705, which in addition to the SPIRE and PACS fluxes includes global fluxes from LABOCA and the Spitzer IRAC and MIPS fluxes from Cannon et al. (2006) to better constrain the mid-IR contribution to the SED, and this global SED is presented in Fig. 2. We used a realistic dust radiation model as far as dust grain properties were concerned, a simpler version of the Galliano et al. (2008) model. The sources of emission are the dust grains (molecules like PAHs, silicates, graphites) and old stars, while the dust composition and size distribution adopted were those of Zubko et al. (2004), with abundances assumed to be solar. The dust optical properties were taken from Draine & Li (2007) for PAHs, Laor & Draine (1993) for graphites and Weingartner & Draine (2001) for silicates. The interstellar radiation field spectral shape was assumed to be that of the Galactic diffuse ISM (Mathis et al. 1993). The Dale et al. (2001) prescription was used to link the dust mass to the integrated radiation density it was exposed to – see Galametz et al. (2009) for a more complete description of the free parameters of the modelling, among those the total dust mass (\(M_{\text{dust}}\)) and the PAH-to-dust mass (\(f_{\text{PAH}}\)) normalized to the Galactic value. To account for the observed excess at submm wavelengths, an additional, independent, modified blackbody was added to the model.

We then proceeded on two fronts in terms of fitting the model to the fluxes – a) letting \(\beta\) vary and keeping the temperature fixed and b) keeping \(\beta\) fixed, and letting the temperature vary. However, we found that when \(\beta\) was allowed to vary with a temperature of the cold dust fixed (10 K), the SED fit had a tendency to find beta values less than 0.5. This unrealistic value of \(\beta\) (normally with values between 1 and 2) (Bolatto et al. 2000) probably reflects instead, a distribution of dust temperatures. As a result of this, we decided to fix the value of \(\beta\) to 1 and let the temperature of the cold dust component vary instead.

The addition of such a dust component (with a temperature of \(\lesssim 10\) K) within the global SED of NGC 1705 has been tentatively suggested previously by Galametz et al. (2009), on the basis of the addition of the 850 μm LABOCA point, with this additional dust component containing up to 70% of the total dust content of the system. There have been significant claims of prior detections of very cold dust components within dwarf galaxies (Galliano et al. 2003, 2005; and Galametz et al. 2009), but the lack of far-IR and sub-mm fluxes to constrain SEDs sufficiently well has left this open to debate. If present, very cold dust can only be found deep in the interior of clouds; it must be protected from stellar light and shielded by an optical depth well above 10 mag. The PACS and SPIRE images provide us with an additional constraint regarding the cold dust, namely it must be located where we see the emission, e.g. the eastern condensation, which strongly is suggestive of high extinction in those locations. With the addition of the three SPIRE photometry points, in particular the 350 and 500 μm points, the claim for an additional dust component is strengthened.

Our best-fit modeling is consistent with the need for an additional cold dust component, and leads to a cold dust mass of \(4.0 \times 10^5\ M_\odot\) with a temperature of the cold dust of 5.8 K (with \(\beta = 1\)). For the warmer dust component, we estimate a dust mass of \(2.1 \times 10^4\ M_\odot\) giving a total dust mass of \(4.2 \times 10^5\ M_\odot\). The plotted fit in Fig. 2 is indeed the best available fit – we attempted to fit a range of dust temperatures to satisfy a reasonable fit to the submillimeter excess. However, it was not until the dust temperatures reached less than 10 K that we began to obtain acceptable fits – we considered a cold dust component fit with a temperature of 10 K and a reduced chi squared value of 1.1 to be the lower limit in terms of an acceptable fit. In terms of obtaining a reasonable lower limit for the dust mass, fitting a cold dust component of 10 K leads to an acceptable reduced chi squared value of 1.1, giving us a cold dust mass of \(1.1 \times 10^5\ M_\odot\) and a total dust mass of \(1.8 \times 10^5\ M_\odot\).

The multiband Herschel observations have allowed us to constrain significantly the SED compared to the previous work of Galametz et al. (2009), where the only sub-mm constraint was the LABOCA flux, allowing us to refine the dust component masses and by extension, obtain new values for the PAH dust and dust to gas ratios. For the \(M_{\text{PAH}}/M_{\text{dust}}\), we get \(\sim 2.3 \times 10^{-4}\) – much lower than the Galactic value, and consistent with the PAH emission deficit at very low metallicity (Madden 2002; Galliano et al. 2003; O’Halloran et al. 2006, 2008). Correspondingly for the dust to gas ratio, we get \(\sim 1.0 \times 10^{-2}\), using the HI mass from Galametz et al. (2009). The derived
the lower end of the chemical evolution model used in Galliano
ues (from using graphites and amorphous carbons) are still at
∼dust-to-gas ratio (ffThese reduced dust masses have the knock-on e
3.2.2. Alternatives to the cold dust component scenario
We must also consider the possibility that the sub-mm excess de-
tected in NGC 1705 is not as a result of an extra dust component.
One hypothesis arguing against such a conclusion is that the sub-
mm excess could originate instead from hot (∼100 K) dust with
a dust emissivity index =1 and the temperature fluctuations of
very small grains (Lisenfeld et al. 2002).

The excess could also be explained through a change in the emmis-
ivity of the cold dust grains. For an example of how the emissivity
may change as we move into differing temperature regimes, Dupac et al. (2003) suggest that β decreases with in-
creasing temperatures, from ∼2 in cold (T ∼ 11–20 K) regions
to 0.8 to 1.6 in warmer regions (T ∼ 35–80 K). In contrast, Paradis et al. (2009) showed that the spectral shape of emmis-
vity is always steeper in the FIR (λ < 600 µm) and flatter in the submm and mm regions. In regions where dust is signifi-
cantly colder in the molecular phase than in the atomic phase, an increase in the emissivity by a factor of ∼3 was detected
only in the FIR, whilst the emissivity for the dust in the atomic
and molecular phases become comparable again in the submm
and mm wavelength range. The observed break in the emissiv-
ity spectrum is in qualitative agreement with the dust emission model of Mény et al. (2007), which invokes quantum effects in
amorphous solids to explain the flatness of the observed submm emission spectrum and also produces a break in the emissivity
slope around 600 µm.

However, one must exercise caution in adopting such an inter-
pretation. Flux uncertainties, especially in the Rayleigh-Jeans
region, can affect the results for the SED fits as far as tempera-
ture and emissivity are concerned, as fitting fluxes near the SED
peak produces inaccurate temperature and dust spectral index
estimates. In addition, line-of-sight temperature (and density)
variations can also affect the SED fitting (Shetty et al. 2009a,b).

Longer wavelength fluxes in the Rayleigh-Jeans part of the spec-
trum (≥600 µm) may more accurately recover the spectral in-
dex, but both methods are very sensitive to noise (Shetty et al. 2009a,b).

An additional alternative to a cold dust component is spin-
ning dust where the rotational dynamics of very small interstellar
gains can explain the 10–100 GHz component of the diffuse
Galactic background via electric dipole rotational emission un-
der normal interstellar conditions (Draine & Lazarian 1998a,b).
However, Jones (2009) notes that observations by Dickinson et al. (2006), which searched for a microwave emission excess in
an H II region, puts an upper limit on the dust emission at
31 GHz and appears to be inconsistent with the spinning dust
model. Given the unsatisfactory evidence arguing against the use of
amorphous carbon to explain the sub-mm excess, we conclude
that the most likely scenario to explain the observed excess is that of an additional cold dust component.

References
Bendo, G. J., Wilson, C. D., Warren, B. E., et al. 2010a, MNRAS, 402, 1409
Bendo, G. J., et al. 2010b, A&A, 518, L65
Bolatto, A. D., Jackson, J. M., Wilson, C. D., & Moriarty-Schieven, G. 2000,
ApJ, 532, 909
Cannon, J. M., Smith, J. D. T., & Walter, F. 2006, ApJ, 647, 293
Dale, D. A., Helou, G., Contursi, A., et al. 2001, ApJ, 549, 215
Dickinson, C., Cassius, S., Pineda, J. L., et al. 2006, ApJ, 643, L111
Draine, B. T., & Lazarian, A. 1998a, ApJ, 494, L19
Draine, B. T., & Lazarian, A. 1998b, ApJ, 508, 157
Draine, B. T., & Li, A. 2007, ApJ, 657, 810
Dupac, X., Bernard, J.-P., Bouden, N., et al. 2003, A&A, 404, 11
Galametz, M., Madden, S., Galliano, F., et al. 2009, A&A, 508, 645
Galliano, F., Madden, S. C., Jones, A. P., et al. 2003, A&A, 407, 159
Galliano, F., Madden, S. C., Jones, A. P., et al. 2005, A&A, 434, 867
Galliano, F., Dwek, E., & Charnail, P. 2008, ApJ, 672, 214
Griffith, M. J., et al. 2010, A&A, 518, L3
Gordon, K. D., Engelbracht, C. W., & Smith, V. V. 2008, ApJ, 682, 336
Heckman, T. M., Sembach, K. R., Meurer, G. R., et al. 2001, ApJ, 554, 1021
Jones, A. P. 2009, A&A, 506, 797
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Lee, H., & Skillman, E. D. 2004, ApJ, 614, 608
Lisenfeld, U., Sievers, A., Israel, F., & Stil, J. 2002, A&A, 382, 860
Madden, S. C. 2002, Ap&SS, 281, 247
Mateau, M. 1998, in The Magellanic Clouds and Other Dwarf Galaxies, Proc.
Bonn/Bochum-Graduiertenkolleg Workshop, ed. T. Richtler, & J. M. Braun
(Aachen: Shaker Verlag), 57
Mathis, J. S., Mezger, P. G., & Panugia, N. 1983, A&A, 128, 212
Meny, C., Gromov, V., Boudet, N., et al. 2007, A&A, 468, 171
Meurer, G. R., Heckman, T. M., Leitherer, C., et al. 1995, AJ, 110, 2665
Meyer, G. R., Staveley-Smith, L., & Kibble, N. E. B. 1998, MNRAS, 300, 705
O’Hlarran, B., Satyapal, S., & Dukid, R. P. 2006, ApJ, 641, 795
O’Halleran, B., Madden, S. C., & Abel, N. P. 2008, ApJ, 681, 1205
Paradis, D., Bernard, J.-P., & Mény, C. 2009, A&A, 506, 745
Pilbratt, G. L., et al. 2010, A&A, 518, L1
Pohlen, M., et al. 2010, A&A, 518, L172
Poglitsch, A., et al. 2010, A&A, 518, L2
Prantzos, N., & Silk, J. 1998, ApJ, 507, 229
Rouleau, F., & Martin, P. G. 1991, ApJ, 377, 526
Serra-Díaz-Cano, L., & Jones, A. P. 2008, A&A, 492, 127
Shetty, R., Kauflmann, J. S., Chene, S., & Goodman, A. A. 2009a, ApJ, 696, 676
Shetty, R., Kauflmann, J., Schnee, S., & Goodman, A. A., & Ercolano, B. 2009b,
ApJ, 696, 2234
Swinyard, B. M., et al. 2010, A&A, 518, L4
Tosi, M., Sesti, E., Bialassini, M. et al. 2001, AJ, 122, 1271
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296
Zubko, V., Dwek, E., & Arendt, R. G. 2004, ApJS, 152, 211

Acknowledgements. SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including
Univ. Leibnizbridge (Canada); NAOC (China); CEA, OAMP (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCLA,
MSSL, UKATC, Univ. Sussex (UK); and Caltech/JPL, IPAC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); Stockholm Observatory (Sweden); STFC (UK); and NASA (USA). PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KUL, CSL, IMEC (Belgium); CEA, OAMP (France); MPIA (Germany); IFSI, OAP/AO, OAA/CAI/SISE, LENS, SISSA (Italy); INAF (Italy); CSIRO (Australia). This development has been supported by the funding agen-
cies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI (Italy), and CIT/IC/ MCT (Spain).

Page 5 is available in the electronic edition of the journal at http://www.aanda.org
