Cold dust clumps in dynamically hot gas*

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ABSTRACT

Aims. We present clumps of dust emission from Herschel observations of the Large Magellanic Cloud (LMC) and their physical and statistical properties. We catalog cloud features seen in the dust emission from Herschel observations of the LMC, the Magellanic type irregular galaxy closest to the Milky Way, and compare these features with H\textsc{i} catalogs from the ATCA+Parkes H\textsc{i} survey.

Methods. Using an automated cloud-finding algorithm, we identify clouds and clumps of dust emission and examine the cumulative mass distribution of the detected dust clouds. The mass of cold dust is determined from physical parameters that we derive by performing spectral energy distribution fits to 250, 350, and 500 \(\mu\)m emission from SPIRE observations using dust grain size distributions for graphite/silicate in low-metallicity extragalactic environments.

Results. The dust cloud mass spectrum follows a power law distribution with an exponent of \(\gamma = -1.8\) for clumps larger than 4\times10^2 M\(_\odot\), and is similar to the H\textsc{i} mass distribution. This is expected from the theory of ISM structure in the vicinity of star formation.

Key words. Large Magellanic Cloud – spectral energy distribution – cumulative mass spectrum – far-infrared – sub-millimeter

1. Introduction

The overall structure and evolution of the ISM of a galaxy is determined by the physical and dynamical conditions in the diffuse ISM where most of the processing of gas and dust clouds occurs. Thus inspecting the cloud properties by studying the atomic gas and the dust emission under different environmental conditions will help us to understand how this processing of matter proceeds.

In the present paper, we study the dynamical conditions of the diffuse gas in the Large Magellanic Cloud (LMC). We examine optically thin dust emission at far-infrared (FIR) and sub-millimeter wavelengths by studying the spectral energy distributions (SEDs) inferred from radiative transfer models. By combining an H\textsc{i} synthesis survey and an imaging survey in the FIR and submillimeter emission performed by Herschel Space Observatory (Pilbratt et al. 2010), we investigate the detailed relationship between the diffuse atomic gas and interstellar dust emission in the LMC. The Herschel Space Observatory is designed to study the submillimeter and FIR emission from our universe and offers unprecedented resolution. The Herschel has a payload of two cameras, PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010). PACS employs two bolometer arrays for imaging, and SPIRE comprises spider-web bolometers with NTD Ge temperature sensors. Mapping strategy and data processing procedures are described in detail by Meixner et al. (2010).

The Herschel survey of the Magellanic Clouds will provide information about the interstellar dust emission (Meixner et al. 2006) from all phases of the ISM in the Magellanic Clouds. For diffuse atomic gas, we use data from the H\textsc{i} aperture synthesis survey in Kim et al. (1998) and data from the combined survey using single-dish observations with the Parkes 64-m radio telescope (Staveley-Smith et al. 2003) that was published in Kim et al. (2003). The SED models provide spectral information in the 160 \(\mu\)m to 500 \(\mu\)m wavelength range. Relatively optically thin dust emission at FIR and submillimeter wavelengths can also provide information about the gas mass in the ISM because the gas and dust are well mixed in most of the ISM phases. Therefore, the dust emission at the FIR and submillimeter wavelengths can trace the column density and the structure of the ISM.

2. Cold dust associated with atomic hydrogen

2.1. Dust clumps

The unprecedented quality of the SPIRE images improves our knowledge of the spatial distribution of galactic infrared/submillimeter dust radiation and characterizes it as cloud features with clumps and filaments. We adopt the ‘clump’ terminology to represent entities with properties of typical ‘clouds’ seen in the molecular clouds in the Galaxy (Bergin and Tafalla 2007). We examine the brightness distribution of the pixels treating them as clumps by searching for peaks of local emission and adding the neighboring pixels of one clump to the objects (Williams, de Geus, & Blitz 1994). We find 7449 dust clumps generated by an automatic clump-finding routine for the 500 \(\mu\)m emission. The threshold being set to three times of an RMS of ~0.3 MJy/sr (Fig. 1). The automatic clump-finding algorithm determines structure by first contouring the data at a multiple of the RMS noise of the data, searching for peaks of emission

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that are local maxima in the SPIRE images, and then connecting pixels at each contour level from the highest to lower intensities. Isolated contours at each level are identified as clumps (Williams, de Geus, & Blitz 1994).

By applying the same method to the 350 μm image of the LMC, we find 8460 dust clumps (Fig. 2). More faint clumps are seen at 350 μm than 500 μm above the noise level. However, the dust clumps at 500 μm are well correlated with the H i clouds and filaments. In general, the dust clumps at 500 μm identified in the present study are distributed quite uniformly in the LMC. Thus, for the clump analysis pursued in this study we use the clumps identified in the 500 μm image.

For a clump consisting of a set of pixels with positions \([x, y]\) and intensity \([I]\), the size of each clump is calculated based on its extent in the spatial dimension below. The clumps range in size from 9.8 to 47±1 pc with a median of 15±1 pc in radius given by

\[
\sigma_r = \left( \frac{\sum I x^2}{\sum I} - \left( \frac{\sum I x}{\sum I} \right)^2 \right)^{1/2}.
\]  

(1)

2.2. Physical properties of dust clumps

Each dust clump was characterized by the radiation source properties associated with the dust clump and their ambient medium using DUSTY radiative transfer calculations performed by Ivezić et al. (1999). This model assumes a spherical geometry and supports an analytical form of the dust density distribution (Sarkar et al. 2006). The physical parameters constrained by fitting the observed SEDs include the chemical composition of the dust, grain size distribution, dust temperature at the inner and outer boundary, dust density distribution, optical depth at a specific wavelength, and the ambient interstellar radiation field (ISRF). We adopted the chemical properties of the dust determined by Draine & Li (2001) and Weingartner & Draine (2001).

For dust in the neutral medium, we adopted the size distribution of Kim, Martin, & Hendry (1994, KMH) using the power law distribution function for grain sizes, \(n(a) \propto a^{-q} e^{-a/a_m}\) with \(q=3.5\), \(a_{mm}=0.005\) μm, and \(a_{max}=0.25\) μm. The classical model of grain size distribution was constructed by Mathis, Rumpl, & Nordsieck (1977, MRN), and Draine and Lee (1984) revised the MRN model with dielectric functions for graphite and silicate (Draine and Li 2001).

Interstellar grain temperatures are calculated from

\[
\int_0^\infty \pi B_\lambda(T_d) Q_{IR}(a, \lambda) d\lambda = \int_0^\infty F_\lambda Q_{UV}(a, \lambda) d\lambda
\]

(2)

where \(B_\lambda(T)\) is the Planck function for dust at temperature \(T\), \(F_\lambda\) is the flux of the interstellar radiation field, and \(Q_{IR}(a, \lambda)\) and \(Q_{UV}(a, \lambda)\) indicate the infrared and ultraviolet absorption efficiencies, respectively, and are functions of the dust grain radius \(a\) (Spitzer 1978). The ISRF is produced by three components: (1) emission from stars, (2) dust emission in the far-IR associated with the heating of interstellar matter by absorption of star light, and (3) the cosmic background radiation (Cox et al. 1986; Chi & Wolfendale 1991; Strong et al. 2000). Unlike the Milky Way, confusion along the line-of-sight to the LMC is negligible because of its low inclination (Weinberg and Nikolaev 2001). The LMC also has low internal reddening, and its proximity permits the detailed study of its stellar population. Therefore, the ISRF in the LMC can be estimated with confidence.

The dust equilibrium temperatures are obtained by determining the energy balance between absorption and emission. In Fig. 3, we present three examples of applying DUSTY to different clumps. The result of each fitting provides a characteristic dust emission temperature, \(T_d\) for each clump and an estimate of the graphite and silicate abundance ratio. The resulting graphite and silicate abundances from fitting the observed SEDs differ by 50% among the clumps in different environments in the LMC. The second approach to characterize clump temperature is to apply GRASIL (Silva et al. 1998). This spectrophotometric
self-consistent model computes the absorption and emission by dust in three different environments such as molecular clouds, diffuse ISM, and AGB envelopes with a dust model consisting of big grains, small grains, and polycyclic aromatic hydrocarbons (PAH) molecules. The consistency check on the equilibrium temperature is made using the GRASIL model and the observed SEDs (Fig. 3). In general, the observed fluxes at 160 – 500 µm are ascribed to the dust in the diffuse medium heated by the interstellar radiation field. Heating of diffuse gas in the ISM can occur by means of the photoelectric heating in interstellar clouds where the dust grains act as catalytic surfaces. The resultant temperature from the fit to the observed SEDs ranges from 15±0.4 to 25±0.4 K and is similar to the SPIRE temperature map (Gordon et al. 2010).

At a given grain temperature, the mass of each dust clump is calculated from \( M_d = S_d \times D^2 / k_d \times B_d(T_d) \), where \( S_d \) is the flux density at 500 µm and \( D \) is the distance of the galaxy at 50 kpc (Schaefer 2008), and \( B_d(T_d) \) is the value of the Planck function at 500 µm, and a function of \( T_d \). We adopt a mean temperature for each clump as a function of the three categories shown in Fig. 3. The YSOs region and bar region in Fig. 3 indicate dynamically hot regions described in Kim et al. (1998, 2007), where \( k_d \) is the mass absorption coefficient at 500 µm from the SPIRE observations and \( k_d \sim 1.15 \text{ cm}^2/\text{g} \) is used. The derived dust masses are in the range of \( 1.8 \times 10^3 M_\odot < M_{\text{dust}} < 7.9 \times 10^3 M_\odot \).

To characterize the clump properties, the mass spectrum of the clumps is examined. We choose the cumulative spectrum rather than the differential mass distribution since the relative masses will be more or less the same, when the mass range is small over the entire spectrum. For each catalog, we fit a power law function to the cumulative mass distribution (Rosolowsky et al. 2005; Kim et al. 2007):

\[
N(M' > M) = N_0 \left( \frac{M}{10 M_\odot} \right)^{\gamma + 1},
\]

where \( N_0 \) is the number of clouds in the derived distribution with masses higher than \( 10 M_\odot \) and \( \gamma \) is the index of the differential mass distribution. The cumulative distribution of dust cores in the catalog of sources identified in this study and the residuals of the fit are presented in Fig. 4. The clump mass spectrum follows a broken power law in the mass distribution. For masses lower than \( 4 \times 10^2 M_\odot \), it follows a power law distribution and decreases slowly with an exponent of the mass distribution, \( \gamma = -0.8 \). For the clumps more massive than \( 4 \times 10^2 M_\odot \), the mass spectrum is significantly steeper with a slope of \( \gamma = -1.8 \pm 0.1 \) than in the lower mass regime. The observed clump mass spectrum for \( 1.8 \times 10^1 M_\odot < M_{\text{dust}} < 4.0 \times 10^2 M_\odot \), exhibits a flatter power law than the stellar initial mass function (Salpeter 1955). This confirms that most of the clump mass resides in massive clumps, while the most of the stellar mass is in low-mass stars (McKee and Williams 1997; Johnstone et al. 2000).

### 2.3. Gas and dust mass spectrum

Observation and analysis of the dust clumps and neutral cloud structure indicate that a number of smaller clumps reside in the neutral diffuse clouds. The physical properties of dust clumps were characterized in terms of their mass spectrum, which follows a power law distribution. We note that the distribution of dust clump mass is quite similar to the H\textsc{i} mass distribution, the index of the mass distribution being, \( \gamma = -1.88 \). The mass of the H\textsc{i} cloud was determined from its integrated intensity \( I \) measured in K km s\(^{-1}\):

\[
M_{\text{cloud}} = 1.822 \times 10^{18} I \sigma_{\text{cl}} m_{\text{H}_1},
\]

where \( \sigma_{\text{cl}} \) is the total cloud area in cm\(^2\). Since the dust emission in the far-IR continuum emission provides an estimate of the star formation rate (SFR) and grains remain strongly coupled to the neutral gas, we expect the mass spectra of the dust clouds to behave in a similar way to the mass spectra resulting in the diffuse gas.

The mass function near the high-end appears to be even steeper with \( \gamma = -2.1 \). The index of that power law fit can be steeper where star formation is ongoing, such that cloud dissipation occurs (Wada et al. 2000). The similarity of clump mass distribution suggests that the overall gas-to-dust mass ratio is more or less uniform in the region considered here. This is consistent with the overall gas-to-dust mass ratio being relatively uniform across the LMC, except for the super-shell affected by the supernova shocks (Gordon et al. 2003). A detailed analysis of the gas-to-dust mass ratio of two molecular clouds in the LMC can be found in Roman-Duval et al. (2010).
Fig. 4. Dust clump mass spectrum (Top). The slope of the mass spectrum, $\gamma$, is -1.8 with an error estimate of $\pm 0.1$. H I clump mass spectrum (Bottom). The slope of the H I mass spectrum, $\gamma$, is -1.88 with an error estimate of $\pm 0.1$ for the fit in the selected mass range.

3. Summary

Dust clumps have been identified and cataloged in the Herschel SPIRE survey of the LMC using an automated cloud-finding algorithm. The distribution of cold dust clumps is remarkably similar to the H I clump mass distribution, sharing an index of mass distribution, $\gamma = -1.8$. However, the dust clump mass spectrum in the lower mass regime follows a flatter power law than the Salpeter stellar IMF.

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