Exploring the Dust Population in Cold Diffuse Clouds

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ABSTRACT

The formation and evolution of cold diffuse clouds (CDCs), the parent objects of dense molecular clouds, affects both the star formation process and that of larger-scale galactic evolution. We have begun a pilot study of one CDC's dust content, with the goal of quantifying the abundances of different types of dust and relating these to the relative abundance of molecular gas, the cloud's physical properties, and its general stage of development. Using photometry from *AKARI* and other surveys, we have extracted a sample spectral energy distribution (SED) of the CDC dust thermal emission over the near-infrared to submillimeter range. The extracted SED closely resembles others in the literature, confirming our isolation of the cloud emission from other sources along the sight line. We plan to fit this SED with dust models at each position in the cloud, automating our procedure to map out the structure of this CDC and others.

Keywords: stars: formation — ISM: clouds — ISM: general — (ISM:) dust — infrared: ISM — radio lines: ISM

1. INTRODUCTION

Cold diffuse clouds (CDCs) are a key transitional phase between the warm, tenuous, ambient interstellar medium of mostly-neutral atomic gas and the colder, denser molecular clouds needed for star formation. However, understanding exactly how CDCs evolve is hampered by observational challenges, as much of their gas is "dark" in H I 21 cm and CO 2.6 mm spectral line emission surveys, while their dust thermal continuum emission can be faint and hard to distinguish from denser clouds in the same sight line. We have developed methods to identify CDCs using H I self-absorption from their cold atomic gas (HISA; **Figure 1**; Gibson 2010), and to isolate their dust emission from confusing backgrounds (Spraggs & Gibson 2016) in order to measure their spectral energy distributions (SEDs) in infrared and sub-millimeter surveys like *AKARI*, *IRAS*, and *Planck* (see **Table 1**). Using SED model fits, we aim to constrain the dust temperature, size distribution, composition, and column density and then examine how these may relate to the H I and H_2 content of the CDCs. For example, emission from large grains in thermal equilibrium relates to both the gas total column density and shielding of the cloud interior, while very small grain (VSG) surfaces are important sites for H_2 formation and photoelectric heating. SED studies can thus inform us of the evolution of the grains within the clouds as well as their effect on the clouds' physical state. We have assembled a number of IR/submm maps of a sample CDC in the outer Galaxy (**Figure 2**) and have begun investigating simple SED model fits for one sight line in this object (**Figure 3**).

2. CURRENT RESULTS

Careful differencing of infrared brightnesses in ON-cloud and OFF-cloud positions (marked in **Figure 2**) yields an SED curve that looks reasonably similar to others in the literature, which should allow detailed constraints on dust SEDs vs. position within CDCs, even for sight lines that include other emission sources.

A preliminary MRN (Mathis et al. 1977) model SED fit of these data (**Figure 3**) shows that the long-wavelength ($\lambda > 80\,\mu$m) brightness is consistent with isothermal large-grain emission in a modified blackbody. At wavelengths just

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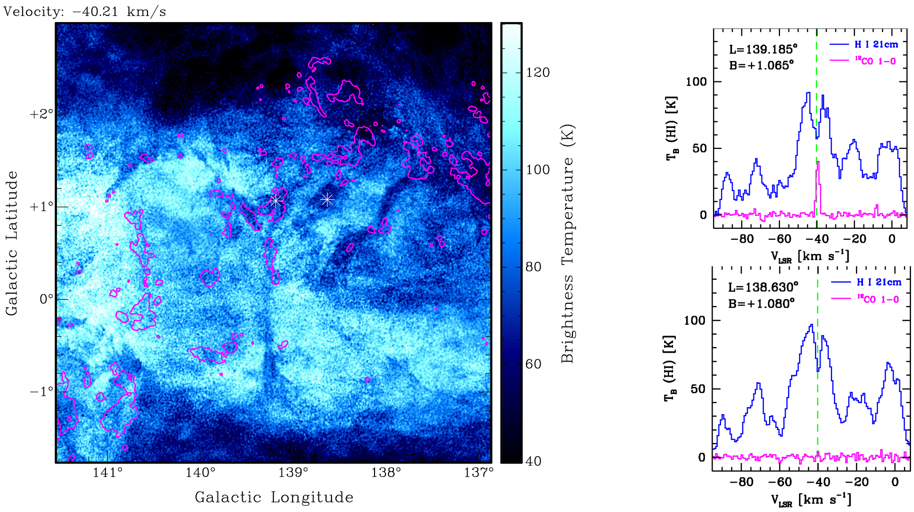

Figure 1. H I self-absorption (HISA) against warmer background H I emission arises from atomic gas that is too cold to explain easily if it is outside molecular clouds (Wolfire et al. 2003), and yet HISA shadows often appear separate from CO emission, particularly in the outer Galaxy (Gibson et al. 2000; Gibson 2010). The panels above show CGPS H I emission and absorption (blue; Taylor et al. 2003) and OGS ^{12}CO $J = 1$–0 emission (magenta; Heyer et al. 1998). These clouds are ~2 kpc away in the Perseus arm, where they may be forming H_2 and CO downstream of the spiral shock before they become dense enough to form new stars Gibson et al. (2005).

below this ($\lambda \sim$ 60–70 μm), very small grains can be fit with a simple MRN power-law distribution. But at shorter wavelengths ($\lambda < 50\,\mu$m), the MRN model lacks sufficient VSG emission and has no polycyclic aromatic hydrocarbons (PAHs) or similar components. A more sophisticated model is obviously needed.

The MRN model H-atom column through the cloud ($N_H = N_{HI} + 2N_{H_2} = 1.3 \times 10^{21}$ cm^{-2}) is broadly consistent with HISA radiative transfer constraints (Gibson et al. 2000) but below that found in combined HISA+CO spectral line analyses (e.g., $N_H > 2.4 \times 10^{21}$ cm^{-2}; Klaassen et al. 2005). However, half of either column may still allow sufficient shielding of the cloud core to reduce heating by external radiation ($A_V \sim$ 0.3–0.6 mag for $R_V \sim 3$ with the Bohlin et al. 1978 conversion factor), thus "hiding" some dust from an isothermal SED fit. This possibility is under investigation.

3. FUTURE WORK

Several steps are planned to put the analysis on a more solid footing. In addition to incorporating other available short-wavelength data (e.g., *WISE*; Wright et al. 2010) and comparing fits for models with more VSG/PAH content (e.g., Draine & Li 2007; Galliano et al. 2011; Jones et al. 2017), we will measure the RMS noise more rigorously, convolve all maps to a common angular resolution, and fit the observed data with synthetic photometry of our SEDs using instrument spectral response curves. We will also automate the OFF region selection and SED fitting map results vs. position throughout a given cloud, using the OFF position selection and interpolation algorithm developed by Spraggs & Gibson (2016), so that gas and dust properties can be studied spatially.

Table 1. Data Sets Used in This Study

Observatory	Instrument	Spectral Band	Beam Size	Surveys/References
DRAO	ST+26m	H I 21 cm line	60″	CGPS[1]
FCRAO	14m	^{12}CO 2.6 mm line	45″	OGS[2], EOGS[3]
Spitzer	IRAC	3.6, 4.5, 5.8, 8.0 μm	2″	(this work)[4]
AKARI	IRC	9, 18 μm	6″	*AKARI* Mid-IR All-Sky[5]
IRAS	SA	12, 25, 60, 100 μm	70″–260″	IGA[6], MIGA[7], IRIS[8]
Spitzer	MIPS	24, 70, 160 μm	7″–47″	(this work)[4]
AKARI	FIS	65, 90, 140, 160 μm	63″–88″	*AKARI* Far-IR All-Sky[5]
Herschel	PACS	70, 160 μm	6″–13″	Hi-GAL[10]
Herschel	SPIRE	250, 350, 500 μm	18″–36″	Hi-GAL[10]
Planck	HFI	350, 550, 850 μm	300″	*Planck* Data Release 2[11]

[1]CGPS: Taylor et al. (2003); [2]OGS: Heyer et al. (1998); [3]EOGS: Mottram & Brunt (2010)
[4]Bell et al. (2012); [5]IRC: Ishihara et al. (2010); [6]FIS: Doi et al. (2015); [7]IGA: Cao et al. (1997)
[8]MIGA: Kerton & Martin (2000); [9]IRIS: Miville-Deschênes & Lagache (2005)
[10]Hi-GAL: Molinari et al. (2010); [11]*Planck* DR2: Planck Collaboration (2016a,b)

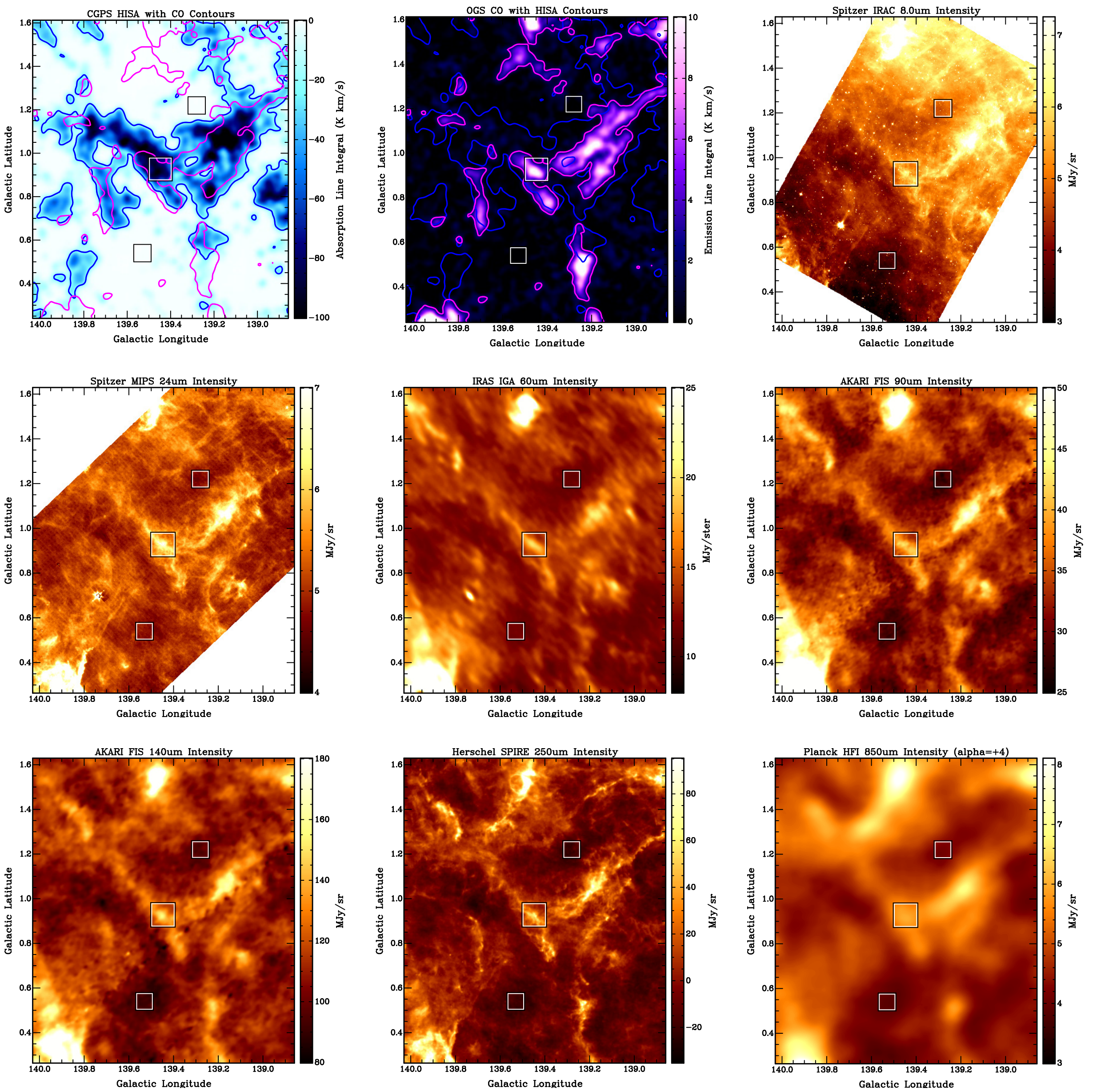

Figure 2. These panels show the region of the current study, which is near the the center of **Figure 1**. *Top left:* smoothed line integral of extracted HISA. *Top center:* line integral of associated CO emission. Other panels show a subset of the dust image data assembled for the same region for λ = 8, 24, 60, 90, 140, 250, & 850 μm; a full list is given in **Table 1**. The boxes mark one ON- and two OFF-cloud areas from which dust emission photometry data were extracted with a 3σ-clipped median statistic; the cloud emission was isolated as the ON minus the averaged OFF brightness, with RMS scatter used as a proxy for measurement uncertainty.

Beyond the basic single-zone dust model, we will explore CDC core shielding effects resulting from different cloud $N_{\rm H}$ columns to check the robustness of the column fits. We will also consider possible dust evolution and its relation, if any, to the CDC evolution or the larger environment. The last will be aided by similar analyses of other HISA CDCs in different parts of the Galaxy, most of which have already been identified (Gibson et al. 2015). Finally, through the use of available all-sky survey data sets, off-plane CDCs showing narrow-line H I emission rather than HISA can be similarly analyzed to provide a more complete view of the CDC population.

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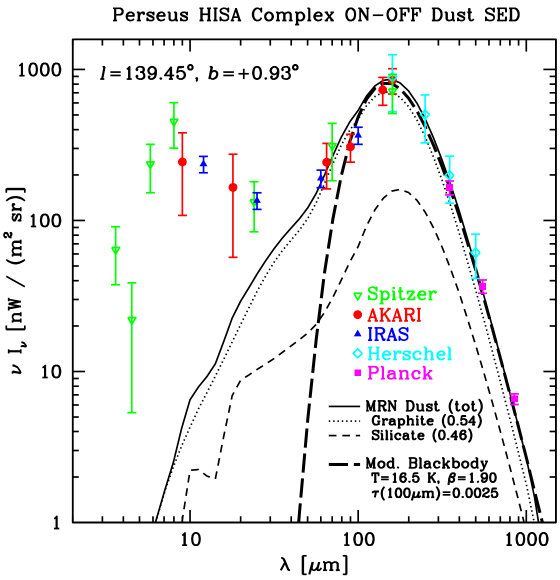

Figure 3. Extracted ON-OFF photometry for the sample sight line taken at the positions marked in **Figure 2** from each of the data sets listed in **Table 1**. A simple SED model with MRN (Mathis et al. 1977) grains is shown for a standard interstellar radiation field (Mathis et al. 1983), gas/dust ratio, and metallicity. This model does not have enough VSGs and lacks PAHs, but it fits the longer-wavelength data better than a modified blackbody. Visual comparison to various other SED measurements and models in the literature (e.g., Compèigne et al. 2011, Fig. 2) highlights the clear detection of many shorter-wavelength features.

project with the participation of ESA. Many data sets were obtained through the NASA/IPAC Infrared Science Archive (IRSA). Data analysis and presentation were aided by the Montage, Miriad, SuperMongo, and Karma software packges.

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