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Very Small Grains in the Milky Way and External Galaxies

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I. Introduction

Excess emission at near- to mid-infrared wavelengths, over that expected from dust grains which are heated in equilibrium with the radiation field, has been observed from astronomical objects ranging from diffuse interstellar clouds to external galaxies. This excess emission has been attributed to a population very small grains (VSGs) which produce the emission in a non-equilibrium process. Theoretical, observational and laboratory studies have suggested that the VSGs may include both Polycyclic Aromatic Hydrocarbon (PAH) molecules (Léger and Puget 1984, Allamandola, Tielens and Barker 1985) and thermally fluctuating small dust grains (Draine and Anderson 1985). Because of the superb sensitivity of the Infrared Astronomical Satellite (IRAS) and its large data sample, IRAS data are very useful for studying this aspect of dust emission.

For many objects of interests, the IRAS 12μm band emission (from 7.5 μm to 15.5μm) arises primarily from the VSG component. The ratio $R = \nu F_\nu(12)/F(\mathrm{farIR})$ is indicative of the ratio of the emission from VSGs to the total far-infrared emission, where F(farIR) is obtained from the IRAS 60 and 100μm fluxes. The ratio $F_\nu(60)/F_\nu(100)$ is taken as a measure of the temperature of larger dust grains which are heated in equilibrium with the radiation field; this ratio is thus indicative of the energy density of the heating radiation.

II. Data Sample and Results

We have measured the IRAS fluxes of 28 visibly bright reflection nebulae illuminated by B stars, by carrying out surface photometry on the co-added IRAS flux density maps. We compare these data with previously published IRAS measurements of high latitude HI clouds heated by the general interstellar radiation field (Heiles, Reach and Koo 1988), and of compact HII regions illuminated by O stars (Antonopoulou and Pottasch 1987). We also discuss in this paper the implication of comparison of infrared colors of these galactic objects with those of external galaxies.

Figure 1 presents a "color-color" diagram, $\nu F_\nu(12)/F(\mathrm{farIR})$ vs $F_\nu(60)/F_\nu(100)$, for several classes of objects, while the mean colors are listed in Table 1. These data show that $< R >= 0.31$ for reflection nebulae and $< R >= 0.38$ for High Latitude (HL) HI clouds, while $< R >= 0.044$ for compact HII regions. The separation between the compact HII regions and the more diffusely heated clouds in Figure 1 is quite striking and apparently independent of the starlight energy density as measured by the 60/100 μm grain temperature. The fact that R in HII regions is about 8 times smaller than in reflection nebulae and HI clouds may be explained in terms of the destruction of VSG's in HII regions or in the immediately adjacent neutral material. This has previously been suggested by Boulanger *et al.* (1988) and Ryter *et al.* (1987) from the studies of the spatial distribution of infrared radiation from extended HII regions. They have shown that the ratio R decreases significantly towards the central ionizing star, where the UV energy density of the stellar radiation field is very high. In the PAH model, this can be interpreted as the breaking of C=H bonds and the suppression of the associated vibrational modes (Allamandola 1988), while in the model of small grains undergoing temperature fluctuations, it implies that smaller grains are preferentially destroyed by hard UV photons or by electron and/or ion impact. A possible alternative explanation of the low value of R for HII regions is that it is due to a high optical depth at $\sim 10\mu$m of the enveloping dust cloud through which the compact HII regions might be viewed in many cases.

Since both HII regions and more diffusely heated material presumably contribute to the infrared radiation from galaxies, we expect the value of R for an entire galaxy Way to lie between those for compact HII regions and for the reflection nebulae and HI clouds. Figure 1 shows that R for a sample of non-interacting spiral galaxies is fairly constant and lies in the expected range. This suggests that: 1) The 12μm band emission seen from these galaxies is predominantly from the VSG population; 2) since R is also proportional to the mass ratio b = Mass(VSG)/Mass(dust), b is approximately uniform in this population of normal spiral galaxies. From the above arguments, we further estimate that R $\sim$ 0.14 for the Milky Way.

We have also extended our investigations into interacting galaxies. The high L(IR)/L(B) (> 35) galaxies studied by Bushouse, Lamb and Werner (1988) have $< R >=$ 0.089. These group of galaxies are merger-type objects, contact pairs or very closely interacting pairs. They have nuclear region optical spectra indicative of high levels of current star-formation activity, with very hot stars being the dominant ionization source. Thus it is not surprising that they have values of R comparable to those seen in the warmer HII regions.

~~III.~~ Summary

~~In summary, our~~ These studies of the infrared colors of reflection nebulae, HL HI clouds, HII regions and external galaxies have shown the following:

1. Different classes of objects locate in different regions on the R vs $F_\nu(60)/F_\nu(100)$ diagram. This is determined both by differences in dust properties and by differences in the illuminating radiation field. For example, HL clouds and reflection nebulae almost have the same behavior since both are in the diffuse ISM and can be expected to have similar grain populations; the small difference in their infrared colors can be explained by the difference of the illuminating radiation field. On the other hand, the dramatic difference of $R = \nu F_\nu(12)/F_\nu(\text{farIR})$ between HII region and diffuse ISM may be due to the destruction of the VSG component in the HII regions, although radiation transfer effects may play a part as well.

interstellar medium (ISM)

2. The ratio $R = \nu F_\nu(12)/F_\nu(\text{farIR})$ is approximately constant in normal spiral galaxies. This implies that the mass ratio b = Mass(VSG)/Mass(dust) is does not vary greatly from one galaxy to another.

~~Further implications of these results and an extension to include the 25*mum* IRAS data in the comparisons will be presented in a more complete paper currently in preparation.~~

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very small grain (VSG)

TABLE 1

MEAN PROPERTIES OF SAMPLES

Sample	$\frac{\nu F_\nu(12\mu m)}{F(FIR)}$ $\pm\sigma$	$\frac{F_\nu(60\mu m)}{F_\nu(100\mu m)}$ $\pm\sigma$	T_{dust}[a]
Reflection Nebulae.......	0.30 ±0.27	0.44 ±0.16	33
HL HI Clouds[b]............	0.38 ±0.21	0.23 ±.057	27
HII Regions[c]................	.044 ±.024	0.58 ±0.15	37
Normal Spiral Galaxies[d]	0.14 ±.057	0.45 ±0.11	34
High L_{IR}/L_B Galaxies[d].	.089 ±.035	0.72 ±0.14	41

Note: [a] Dust temperature computed from the 60/100 μm flux ratio assuming emissivity proportional to frequency. [b] From Heiles, Reach and Koo (1988). [c] From Antonopoulou and Pottasch (1987). [d] From Bushouse, Lamb and Werner (1988).