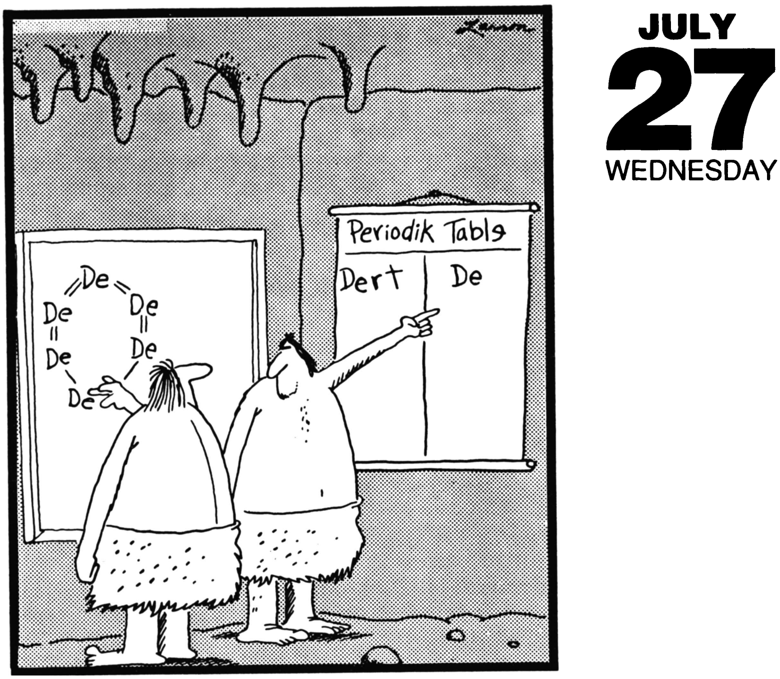
Section II

The Overidentified Infrared Emission Features



Early chemists describe the first dirt molecule

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INFRARED EMISSION FROM REFLECTION NEBULAE

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ABSTRACT. Observations of 1–25 μm continuum emission and the interstellar infrared emission features in reflection nebulae are reviewed. These observations place important constraints on models of very small grains or large molecules such as PAHs, which these models must address in order to understand this fundamental component of interstellar dust.

1. THE NEAR IR CONTINUUM IN REFLECTION NEBULAE

Near infrared continuum emission was first detected at 1–5 μm in reflection nebulae, along with the 3.3 μm emission feature, by Sellgren, Werner, and Dinerstein (1983). This continuum in reflection nebulae was found to extend over at least 1–13 μm by Sellgren *et al.* (1985). The continuum is far in excess over expected levels of reflected light or thermal emission from dust in equilibrium with the radiation field. The continuum is characterized by a high color temperature ($\sim$ 1000 K) at 1–5 μm, yet the surface brightness distribution of the near infrared continuum emission follows that of the visual scattered light, suggesting that the near infrared emission is radiatively excited. The continuum color temperature and the 3.3 μm feature-to-continuum ratio are the same in all nebulae, independent of distance from the star. The 3.3 μm feature detected in reflection nebulae is one of six emission features at 3.3, 3.4, 6.2, 7.7, 8.6, and 11.3 μm, which have been reviewed by Aitken (1981), Willner (1984), and Bregman (1989).

Sellgren (1984) has proposed a model in which the near infrared continuum emission in reflection nebulae is due to non-equilibrium thermal emission from very small grains (10 Å radius) which are briefly heated to high temperatures by the absorption of single UV photons. Léger and Puget (1984) and Allamandola, Tielens, and Barker (1985) have identified the infrared emission features with UV-excited vibrational fluorescence from polycyclic aromatic hydrocarbons (PAHs), large molecules similar in size to the very small grains proposed by Sellgren (1984).

The size of the particle, whether very small grain or large molecule, which emits in the near infrared continuum and features can be estimated from the characteristic temperature of the emission and the wavelength of the exciting stellar photon. The following calculation treats the small particle as a grain (Sellgren, 1984), but very similar results are found for PAHs using a molecular physics approach (Allamandola, Tielens, and Barker, 1985). The energy absorbed by the particle is E_{ph}, the energy

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of the stellar photon. The energy reradiated by the particle is $\int C_V(T)dT$, where $C_V(T)$ is the heat capacity of the particle at the temperature T of the particle. The limits of integration are T_{min}, the temperature of the particle before it absorbs the stellar photon, and T_{max}, the maximum temperature the particle reaches after absorption of the stellar photon. In reflection nebulae the shape of the 1–5 μm continuum suggests $T_{max} \sim 1000$ K, above the Debye temperature of most materials, and so the heat capacity can be approximated by $C_V = 3Nk$, where N is the number of atoms or molecules in the particle and k is the Boltzmann constant. Thus we have $E_{ph} \approx 3Nk(T_{max} - T_{min}) \approx 3NkT_{max}$. For a 1000 Å UV photon and $T_{max} \sim 1000$ K, the number of atoms or molecules in the particle is $N \sim 50$.

2. IRAS OBSERVATIONS OF REFLECTION NEBULAE

The infrared energy distribution of reflection nebulae shows that only a few percent of the total infrared emission is radiated at 1–5 μm by the very small particles (Sellgren, 1984). However, up to 30 % of the total infrared energy emerges as very small particle emission at 12–25 μm (Castelaz, Sellgren, and Werner, 1987). The 12 μm band of the IRAS satellite contains contributions from the 7.7, 8.6, and 11.3 μm emission features, as well as from the associated continuum emission which extends throughout the IRAS band.

Castelaz, Sellgren, and Werner (1987) have studied the spatial distribution of the IRAS emission from the reflection nebula illuminated by 23 Tau. They show that the ratio of 12 μm to 25 μm surface brightness is constant with distance from 23 Tau, as predicted by the very small particle emission model. The dust temperature derived from the ratio of 60 μm to 100 μm surface brightness, in contrast, decreases with distance from 23 Tau, as expected for thermal emission from larger dust grains in equilibrium with the radiation field of the central star. Luan *et al.* (1988) have extended these spatial studies to other reflection nebulae, and find similar results.

Sellgren *et al.* (1988) have obtained IRAS observations of a sample of reflection nebulae whose illuminating stars have temperatures $T_\star$ of 3,000–21,000 K. These observations should determine the energy of stellar photons which are most efficient at exciting the very small particle 12 μm emission, and should constrain the composition of the particles by determining at which UV and visual wavelengths the particles absorb starlight. Scans were obtained along lines passing through the illuminating star, at 12, 25, 60, and 100 μm, from either co-added images or from co-added Addscan data, for a sample of reflection nebulae. A local background level was subtracted from each scan. These data were used to produce scans of T_d, the dust temperature derived from the 60 μm to 100 μm flux ratio. Nebulae in which T_d did not peak on the illuminating star of the reflection nebulae were rejected from the sample, to insure that all nebulae studied were indeed excited by the central star. The scans at 12, 25, 60, and 100 μm were used to obtain surface photometry at offsets from the star of 3–10′, or 0.1–3 pc at the distances of these nebulae.

Figure 1 shows the ratio of the 12 μm surface brightness to the total far infrared surface brightness, plotted against $T_\star$ (Sellgren *et al.*, 1988). The surface brightness units at 12 μm, $\nu I_\nu(12\,\mu\text{m})$, measure the energy per unit frequency interval. The total far infrared bolometric surface brightness, $I_{bol}(\text{FIR})$, is the integral over all wavelengths of a greybody of temperature T_d, modified by a $1/\lambda$ emissivity law, and normalized to the 60 and 100 μm surface brightness. Thus $\nu I_\nu(12\,\mu\text{m})/I_{bol}(\text{FIR})$

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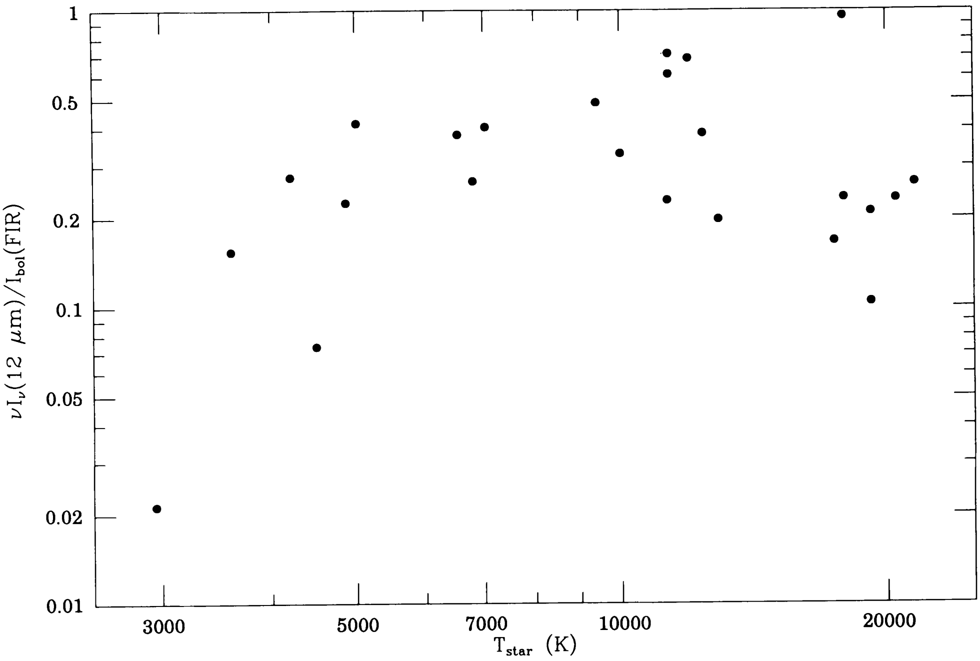

Fig. 1. The ratio of the 12 μm surface brightness, $\nu I_\nu(12\,\mu\mathrm{m})$, to the total far infrared surface brightness, I_{bol}(FIR), plotted against $T_\star$, the temperature of the illuminating star, for a sample of reflection nebulae. From Sellgren *et al.* (1988).

measures how much energy is radiated by the very small particles at 12 μm, relative to the larger grains which account for most of the total infrared emission.

The observed value of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ is $\sim$ 0.3. This implies that roughly 20 % of the total infrared emission of reflection nebulae is radiated at 12 μm. When emission at 1–5 μm and 25 μm is included, the fraction of the total infrared emission due to very small particle emission is $\sim$ 35 %. Very similar ratios of 12 μm emission to total infrared emission are observed in the infrared cirrus (Weiland *et al.*, 1986) and in the diffuse emission of the Galaxy (Boulanger and Pérault, 1988). Thus the very small particles are seen to be very important contributors to the energetics of interstellar dust not only in reflection nebulae, but throughout the interstellar medium.

If the 12 μm emission is only excited by UV radiation, then one expects the ratio of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ to drop markedly for nebulae illuminated by cooler stars, as the fraction of total stellar energy emitted at UV wavelengths drops. Instead, the ratio of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ is roughly constant for nebulae illuminated by stars with temperatures between 5,000 and 21,000 K. There may be some sign of a decrease for the nebulae illuminated by the coolest stars, $T_\star \sim$ 3,000 K, but such a turnover is based only on observations of two nebulae.

The data shown in Figure 1 are clearly inconsistent with the 12 μm emission of reflection nebulae being only excited by UV radiation at $\lambda = 0.1$–0.2 μm; the fraction of stellar luminosity emitted at UV wavelengths drops dramatically to very low values for stars cooler than about 10,000 K. The ratio of 12 μm emission to total infrared emission, observed to be constant over a factor of ≥ 4 in stellar temperature, suggests that the 12 μm emission of reflection nebulae must be excited by stellar photons not just at UV wavelengths, but over a wide range of wavelengths. Luan *et al.* (1988) have compared models of very small particle emission to the observations of Figure 1. They find a reasonable fit if stellar photons throughout the visual and UV range excite the 12 μm emission, but a very poor fit if only UV photons with $\lambda \leq 0.25$ μm are able to excite the 12 μm emission.

The dust emitting at 60 μm and 100 μm in all of these reflection nebulae is clearly heated by the central star of the nebula, because of the requirement that T_d peaks on the central star in these nebulae. The near infrared emission from reflection nebulae illuminated by B stars is also clearly excited by the central star, based on the spatial distribution (Sellgren, Werner, and Dinerstein, 1983; Sellgren, 1984). However, in reflection nebulae illuminated by cooler stars, the very small particles emitting at 12 μm could be excited by another source of radiation, such as the interstellar radiation field. Sellgren *et al.* (1988) argue this is unlikely, because if this were the case there would be no correlation between $\nu I_\nu(12\,\mu\mathrm{m})$ and $I_{bol}(\mathrm{FIR})$ for the nebulae illuminated by cooler stars, while a relatively constant ratio of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ is observed for these nebulae. The total stellar energy densities at the observed nebular positions are generally much larger than the energy density of the interstellar radiation field, for all of the nebulae observed. However, for the coolest stars, while their total energy density is high, the fraction of this energy density due to UV radiation is small. The possibility cannot yet be ruled out that the interstellar radiation field may in fact dominate the 12 μm excitation in the nebulae illuminated by cooler stars, and that it is simply fortuitous that the value of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ in these nebulae is similar to values observed in other nebulae where the excitation of both near and far infrared radiation is clearly due to the central star. This problem needs further investigation.

The 12 μm observations in these reflection nebulae have some important implications for the very small particles. The high value of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ shows that the very small particles are responsible for ~ 35 % of the total infrared emission of reflection nebulae. By conservation of energy, this implies that the very small particles must *absorb* ~ 35 % of the total stellar energy which is absorbed and reradiated by dust. No single UV or visual absorption feature, or group of absorption features, is able to account for such a large fraction of the total absorption of dust. This suggests that the absorption of the very small particles must be broad band in nature, in order to be consistent with the observed interstellar extinction curve. The observed constancy of $\nu I_\nu(12\,\mu\mathrm{m})/I_{bol}(\mathrm{FIR})$ with temperature of the exciting star, if shown to be correct for the nebulae illuminated by cooler stars, also points to excitation of the very small particles over a broad range of wavelengths, rather than absorption which is only efficient in a narrow range of UV wavelengths.

3. CHALLENGES FOR MODELS

The observations of 1–25 μm emission from reflection nebulae present several interesting problems, which any model of interstellar dust must address.

1. Current models of very small particles have focused almost exclusively on the interstellar infrared emission features, yet the 1–25 μm continuum emission provides the most stringent constraint on the particle size, and comprises a larger fraction of the total dust emission than the six features themselves. Observationally, the continuum is very strongly associated with the features (Sellgren, Werner, and Dinerstein, 1983), so that any identification of, or model for, the emission features must therefore explain the 1–25 μm continuum emission equally well.
2. The large fraction of total infrared emission due to the very small particle emission, $\sim$ 35 %, implies that $\sim$ 35 % of the total stellar radiation absorbed by dust is absorbed by the very small particles. Any material proposed to be responsible for the emission features or associated continuum must have UV and visual absorption properties consistent with absorbing such a large fraction of the total starlight absorbed by dust, and also consistent with observations of the interstellar extinction curve.
3. The fraction of total infrared emission emitted at 12 μm appears to be independent of the temperature of the exciting star, although the role of the interstellar radiation field in providing additional 12 μm excitation for nebulae illuminated by cool stars must still be investigated. This constant ratio of 12 μm to far infrared emission, if correct, suggests that the excitation of the 12 μm emission occurs over a broad range of visual and UV wavelengths, rather than a narrow range of UV wavelengths. This suggestion, and the large fraction of total infrared emission due to the very small particles, together imply that the very small particles must contribute broad band absorption throughout the visual and UV range rather than being due to a single absorption feature or group of features. Again, any proposed identification for the near infrared emission features and associated continuum must have absorption properties consistent with these observations.

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