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Research Note

Nature of very small grains: PAH molecules or silicates?

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Summary. The predictions of the model of Puget et al. (1985) for the emission from Very Small Grains (VSGs) including both graphitic (PAHs) and silicate components are compared with published 8–13 μm observations of astronomical sources. *The VSGs are found to be mainly graphitic* and an upper limit is placed on the relative mass of silicates based on lack of the 9.7 μm silicate emission feature on M82 and NGC2023. This dissymetry in the composition of VSGs supports the suggestion that they are formed in *grain-grain collisions* where the behaviors of graphite and silicate grains are expected to be quite different.

Key words: Infrared radiation – interstellar medium: dust, general

1. Introduction: nature of very small grains

As reviewed by Puget, Léger, and Boulanger (1985, hereafter PLB), there is now strong evidence favoring the existence of very small grains (VSGs) in the interstellar medium. Support to this assumption comes mainly from the analysis of near and mid infrared (2–15 μm) spectra of various astrophysical objects, among which reflection nebulae (Sellgren et al., 1983), planetary nebulae, H II region, extended emission in our Galaxy (Price, 1981), the IRAS cirrus clouds and starburst galaxies as a whole (e.g. M82). When spectroscopic data on these objects are available, they exhibit a continuum and proeminent emission bands at 3.28, 6.2, 7.7, 8.6, and 11.3 μm. The challenge was to explain the two features, including their emission mechanism.

Duley and Williams (1981) showed that CH groups, chemically bound to graphitic grains would have vibrational modes precisely at 3.3 and 11.3 μm. However, the origin of the other bands was not clear and the excitation mechanism (Dweek et al., 1980) required grain temperature much higher than could be reached at equilibrium, in the regions where the emissions are observed.

On the other hand, Sellgren (1984) showed that VSGs transiently heated to high temperature by single photon absorption can explain the continuum emission. In order to emit efficiently at 2–4 μm, the VSGs must have excursions at temperatures of about 1000 K. Their nature was not specified.

Léger and Puget (1984) argued that graphitic VSGs, but not silicate ones, would survive from sublimation during such repeated hot events. They also showed that the graphitic VSGs should be Polycyclic Aromatic Hydrocarbon (PAH) molecules. This synthesis of the preceding ideas leads to an impressive spectroscopic agreement between the absorption bands of a typical PAH, coronene, and the five observed emission bands. They could also account for the intensity of the features with a few percent of the cosmic carbon in PAHs.

PLB (1985) calculated the infrared emission of a grain population that includes PAH molecules and predicted an emission in the 12 μm IRAS band for the cirrus clouds which do not contain any internal heating sources. This emission has been observed (Boulanger et al., 1985) and is now overwhelming in the IRAS maps. No big grain (of radius more than 10 nm) can contribute significantly to these wavelengths, because they are too cold ($T < 50$ K).

However, the argument of Léger and Puget on the resistance to sublimation does not apply to the 10 μm region (8–15 μm) where grain temperatures of only 300 K are required. The emission at these wavelengths could be partly due to silicate VSGs, as was proposed by Draine and Anderson (1985). Therefore a question appears: what is the actual abundance of silicate VSGs relative to PAH molecules?

2. Spectral signatures of very small grains

To investigate the nature of VSGs, we have used the dust model of PLB, and included populations of silicate and graphitic grains. For each type of grain, the assumed size distribution is a power-law with an exponent −3.5 (Mathis et al., 1977) and includes VSGs. The total abundance of graphite grains relative to hydrogen is 3.5 10^{-3} by mass and 6 10^{-3} for silicates (Draine and Lee, 1984). The big grains either graphite or silicates (radius between 1.5 nm

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and 0.25 µm) are taken to emit essentially at their equilibrium temperature. Emission from VSGs (radius between 0.4 nm and 1.5 nm) is approximated by the single photon absorption process (see PLB). The PAH emissivity has been taken from laboratory measurements on coronene, a typical PAH molecule (Sadtler Infrared Spectra, 1959). We allowed a variation of the bandwidths, at fixed position and integrated intensity, and of the relative number of C–H/C–C bonds to fit the emission profile of the Orion bar (Aitken, 1981; Bregman et al., 1984), the only exception is the γ C–H mode that we have moved from 11.9 to 11.3 µm for reasons explained in Léger and Puget (1984). For silicates, we have used the emissivities given by Draine and Lee (1984). The incident radiation field is taken to be the solar neighbourhood one (Mathis et al., 1983).

Let us denote by Y_g the fraction of carbon mass in PAH molecules relative to the carbon mass in graphits grains and Y_s the fraction of silicate mass in VSGs. PLB found that, in order to explain the IR emission of the reflection nebula NGC 7023 (Sellgren et al., 1983), $Y_g = 3\%$. The figure shows the results of the model for two cases: a) $Y_g = 3\%$ and $Y_s = 0$, b) $Y_g = 0$ and $Y_s = 3\%$. The level of each VSG contribution is directly proportional to the corresponding abundance Y. For comparison, the spectra of the galaxy M 82 (Willner et al., 1977, Gillet et al., 1975) and of the reflection nebula NGC 2023 (Sellgren et al., 1985) are also shown in the figure.

Clearly, *the observed spectra in this 3–15 µm region are better interpreted by the emission from PAHs rather than from small silicates*, because they are dominated by the PAH signatures (at 3.3, 6.2, 7.7, 8.6, 11.3 µm). *Small silicates would give a strong 9.7 µm emission* as can be seen in the figure (dashed curve *b* of the figure), or in the spectrum obtained by Draine and Anderson (1985), but *this is not observed* in the astronomical spectra presently available: M 82 and other bright spiral galaxies (e.g. Roche and Aitken, 1985), reflection nebulae: NGC 2023, 7023, and planetary nebulae: NGC 7027, dust around HD 44179, the Orion bar ...

Let us discuss the two examples in more details (see the figure). There have been two interpretations proposed for the 8–13 µm spectrum of the galaxy M 82, (see also other starburst galaxies (Roche and Aitken, 1985)): 1. a deep silicate absorption at 9.7 µm, on a strong continuum defined by the 8 µm and 12 µm points (Frogel et al., 1982), or 2. emission features emerging from a much lower continuum level (Aitken et al., 1981). We think that the assumption (2) is more likely to be correct because of the overall shape of the spectrum. Indeed, the stellar continuum goes down between 1.5 to 5 µm, dust (VSGs) emission can explain the various features, and the rise of the continuum level between the mid infrared and 100 µm is due to dust emission (big grains). Therefore, it seems that the continuum level has a well defined minimum around 5.5 µm. In addition, interpretation (1) implies a silicate optical depth ($\tau \sim 1.5$) corresponding to a visual extinction A_v larger than 15, which is in conflict with the value derived from emission lines ($A_v \sim 4.4$, Aitken et al., 1981; Fogel et al., 1982).

As we observe PAHs in emission in M 82, we should also observe the emission of silicate VSGs if present but if it was hidden by a strong foreground absorption precisely at the same wavelength (9.7 µm). The above discussion indicates that such an absorption is unlikely. The trough at 9.7 µm gives therefore a tentative upper limit on the fraction of mass of silicates which are VSGs: $Y_s < 1\%$. Equivalently, with our model we find for VSGs a mass fraction of silicates relative to graphitic materials smaller than 0.56 whereas it is 1.7 for big grains.

The second example is the reflection nebula NGC 2023. Since most of the heating source comes from the visible illuminating star, the emitting VSGs cannot be burried in the cloud and there is no ambiguity for emission vs. absorption. Unfortunately, the spectrum (Sellgren et al., 1985) is not very detailed around 9.7 µm. The presently available data also point to an upper limit $Y_s < 1\%$.

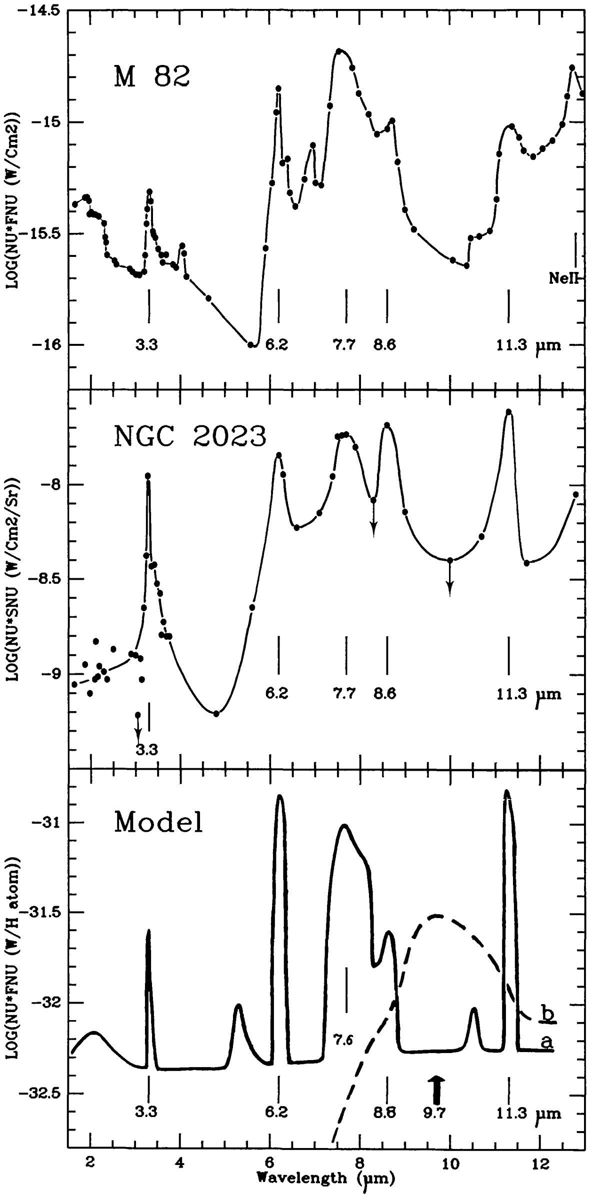

Fig. 1. Mid-infrared spectra (1) of the starburst galaxy M 82, adapted from Willner et al. (1977) and Gillet et al. (1975), (2) of the reflection nebula NGC 2023, adapted from Sellgren et al. (1985) (for both observed spectra, the continuum line between measured points is a smooth interpolation, done only for clarity), and (3) resulting from the emission of very small grains either made of PAH molecules (a) or silicates (b)

It should be noted that in some objects, as planetary nebulae which show the Aromatic Emission Features, the interstellar matter has probably condensed in a carbon rich environment and contains no silicate grains at all (see Barlow, 1983). We can conclude that the absence of silicate VSGs is due to a cut-off in the size distribution in H II regions, reflection nebulae and possibly external galaxies where we have independent evidence of silicate grains.

3. Conclusions and formation mechanism of the very small grains

We have used the dust model of PLB and included possible silicate VSGs. By comparing the resulting 3–15 µm spectrum to that of astronomical objects, we have found that *there is presently no evidence for the presence of silicate VSGs* and derived an upper limit for their abundance. On the other hand, there exists strong evidence for PAH molecules.

This is perhaps linked to the formation mechanism of the VSGs and the major difference in the structure of those two solids. Graphite has a 2-dimension structure. Its binding energy per atom is two orders of magnitude larger inside the C planes than between these planes (see Omont, 1985). In contrast, silicate grains are most probably 3-dimensional with rather strong bonds in any direction. As suggested by Omont (1985), the source of VSGs could be disruption of grains during grain-grain collisions. If the heating during the collision is sufficient, there is vaporisation of the atoms (Duley and Williams, 1984); if it is weaker, it will have no effect on silicates whereas it can *split out the graphitic planes*, and likely sructures of the remaining pieces are precisely PAHs. Another possibility is that all VSGs are severely eroded in the interstellar medium, but graphitic grains are efficiently reconstructed by addition of C^+ ions, whereas a similar reconstruction mechanism does not exist for silicates. *The composition PAH/silicate, of the VSGs perhaps gives us the key of their formation.*

However, our conclusions need to be confirmed by further observations in the 8–12 µm region, especially of reflection nebulae because the interpretation is quite unambiguous for these objects. Spectrophotometry of the cirrus clouds and IRAS extragalactic objects with a strong $F_{12\mu}/F_{100\mu}$ ratio would constitute a very good test of the generality of our derivation.

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