

# CHARACTERISTICS OF INTERSTELLAR AND CIRCUMSTELLAR DUST

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**ABSTRACT:** This paper reviews our current knowledge of interstellar and circumstellar dust from an observational point of view. It is concluded that interstellar dust is highly heterogenous. It consists of a large number of different materials formed in a great variety of stellar birthsites under varying conditions and each with a highly isotopically anomalous composition in its main elements.

## 1. The Carbonaceous Components of Interstellar Dust

Various dust components have been identified in the interstellar medium (ISM). Interstellar silicates make up about 30% of the total dust volume. The remainder has to be carbonaceous in nature and graphite, amorphous carbon, Polycyclic Aromatic Hydrocarbons (PAHs), and organic grain mantles have been suggested<sup>1</sup>. Although notably uncertain, the total identified dust volume seems to fall short of the total dust volume required to explain the interstellar extinction curve and a yet unidentified dust component might be important in the ISM (ie., diamonds<sup>2</sup>).

1.1 *Organic grain mantles and the 3.4 $\mu$ m absorption feature.* A weak absorption feature at  $\approx 3.4\mu\text{m}$ , observed in the interstellar medium (ISM), is very characteristic for saturated aliphatic hydrocarbons (fig. 1), but its detailed substructure is poorly fit by normal paraffins (eg.,  $\text{CH}_3(\text{CH}_2)_n\text{CH}_3$ ) and instead indicates the presence of nearby (but not adjacent) electronegative groups. A particular good (but non-unique) fit in peak position and width is obtained with the spectra of alcohols<sup>3</sup> (fig. 1). Clearly, the resolution and quality of this data is so high that the presence of a feature near  $3.4\mu\text{m}$  in laboratory spectra cannot be claimed as an identification anymore ! Thus, for example, hydrogenated amorphous

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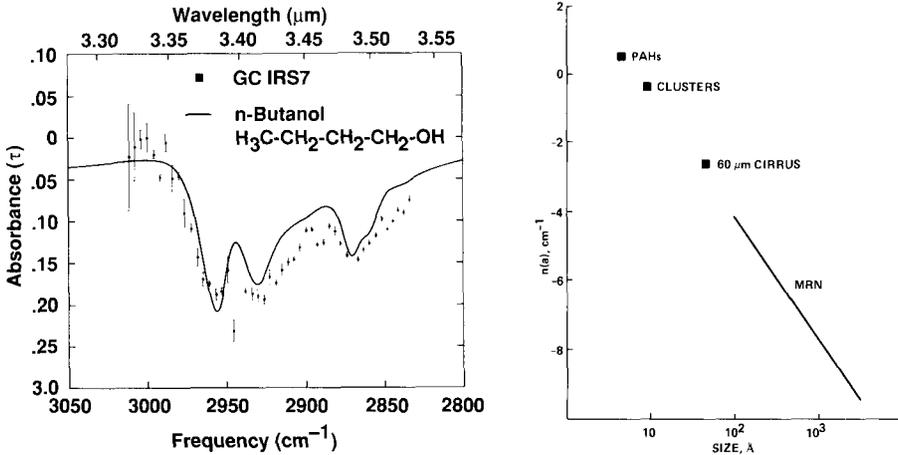


Fig. 1 (Left): The 3.4 $\mu$ m feature in the ISM is fit remarkably well by the CH<sub>2</sub> & CH<sub>3</sub> stretching modes in butanol [3].  
 Fig. 2 (Right): The grain size distribution derived from observations [16].

carbon, a-C:H or HAC<sup>4</sup>, can be ruled out as its carrier. High resolution 5-8 $\mu$ m studies will be important for further characterization of this dust component. Although uncertain, the derived total volume for these organic grain mantles is only about half that of silicates and it does not appear to dominate interstellar dust<sup>1</sup>. Further observations along many more lines of sight will be very important to study its galactic distribution.

**1.2 Graphite and the 2200Å bump.** The 2200Å bump in the interstellar extinction curve has been traditionally identified with graphite<sup>5</sup> and most interstellar dust models are based upon that premise<sup>6,7</sup>. Small graphite spheres ( $a \approx 200\text{\AA}$ ) or "flakes" (axial ratio  $\approx 1.6$  and  $a < 50\text{\AA}$ ) provide an excellent fit to the observed profile<sup>8</sup>. Moreover, graphite grains - with an anomalous isotopic composition betraying a stardust origin - have been isolated from carbonaceous meteorites<sup>9</sup>, providing some support for this assignment. However, the calculated 2200Å profile (i.e., peak position and width) for graphite grains depends strongly on the grain characteristics (i.e., shape and size) and thus should vary widely in the galaxy. Indeed, the width is observed to vary by 25%, but the peak position is constant to within 0.1%<sup>10</sup>. This invariance in the peak position actually forms a problem for any material (i.e., amorphous carbon, silicates). Given the abundance constraints, the 2200Å bump has to be due to an

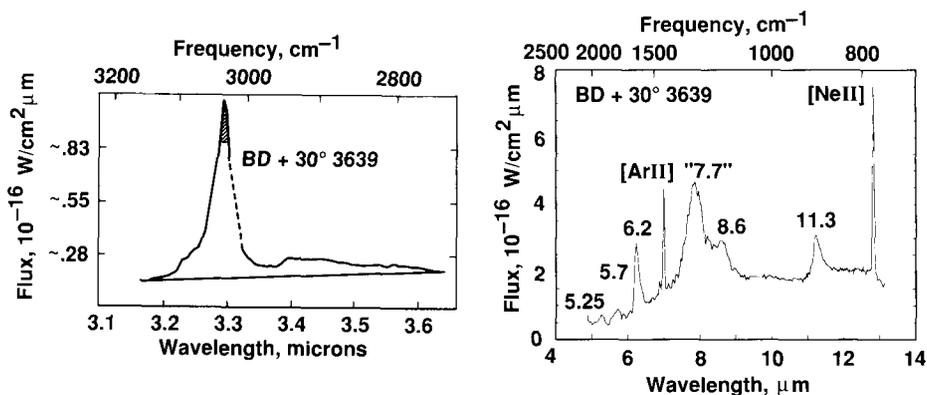


Fig. 3: The planetary nebula BD +30°3639 shows a rich spectrum of IR emission features due to PAH molecules [12].

intrinsically very strong transition<sup>9</sup>. Therefore, its peak position should be very sensitive to surface modes effects and thus to particle shape<sup>11</sup>. This implied shape selectivity in the ISM suggest we may be missing an important point (eg., C<sub>60</sub> ?).

1.3 *PAHs and the IR emission features.* IR spectra of many interstellar and circumstellar sources are dominated by emission features at 3.3, 6.2, 7.7 and 11.3 μm, which are very characteristic for aromatic hydrocarbon materials<sup>12</sup> (fig 3). Since they are also observed in regions far from the illuminating star, the equilibrium dust temperature cannot possibly be high enough to cause emission around 3 μm. Consequently, the emission process has to be non-thermal in origin; ie., absorption of a single UV photon, highly excites the carrier which then relaxes rapidly through the emission of IR vibrational photons (the emission features). This constraints the carrier to small sizes (≈50 C-atoms); ie., PAH molecules consisting of a planar, hexagonal C lattice with peripheral H atoms<sup>12</sup>. There is very good spectroscopic agreement between observed interstellar spectra and laboratory spectra of a collection of PAHs<sup>12</sup>. Indeed, based upon the PAH hypothesis, weak overtone and combination bands were predicted in the 5-6 μm range and these have subsequently been observed<sup>13</sup>. Nevertheless, it should be emphasized that spectroscopic analysis of the observed features mainly implies an aromatic hydrocarbon structure and the molecular character of the carrier is inferred indirectly from an analysis of the energetics. In some sources, the observed spectra also show

broad plateaus underlying these narrow emission bands<sup>12</sup>. Again based upon energetics, these are attributed to somewhat larger aromatic hydrocarbon units (ie., PAH clusters) containing  $\approx 500$  C atoms ( $\approx 10\text{\AA}$ ). The spectra of some sources are dominated by these broad plateaus<sup>14</sup> and their study may help further elucidating their carrier. Likewise, IRAS observations of the ISM reveal a contribution from a dust component with a fluctuating temperature<sup>15</sup> at  $60\mu\text{m}$  (ie., a size of  $\approx 50\text{\AA}$ ) and the interstellar grain size distribution extends smoothly into the molecular domain (fig. 2)<sup>16</sup>.

## 2. The Composition of Stardust

There is a bewildering zoo of objects known to form dust in their outflows or ejecta, including M-, S-, and C-giants, supergiants, planetary nebulae, novae, RCB stars, WC stars, and type I and II supernovae (SN)<sup>17,18</sup>. Among the identified stardust components are silicates, amorphous carbon, PAHs, and oxides. Although these dust components are generally identified by a generic name (ie., silicates), they are formed under distinctly different conditions in the various objects and thus will differ in their detailed composition and structure (ie., mineralogy). For example, C-dust formation in red giant outflows will resemble soot formation in laboratory hydrocarbon flames, resulting in highly hydrogenated C-dust. In contrast, H is absent in the WC star outflows and their dust is probably similar to that formed in laboratory laser vaporization experiments on graphite<sup>18</sup>. Likewise, the Fe/Mg ratio is  $\approx 1$  in M-giants, but  $\ll 1$  in Si-rich zones of SN and this will be reflected in the silicate mineralogy. This may actually have some bearing on silicate compositions measured in Halley<sup>19</sup>. There is also some observational support for such variations. Thus, while most M-giants show a broad and structureless  $10\mu\text{m}$  band (ie., amorphous silicates, but see below), some show evidence for crystalline olivine or aluminous oxides/aluminates<sup>20,21</sup>. Further spectral and compositional characterization of stardust in its various birthsites is an important goal of the next decade.

Each of these stardust birth sites has an anomalous isotopic composition in the main dust forming elements as well as many others<sup>17</sup>. For example, M-giants are enriched in  $^{17}\text{O}$  (and  $^{13}\text{C}$  and  $^{14}\text{N}$  by factors up to 10 due to dredge up from the H-burning shell (CNO cycles)<sup>22</sup> and this will have been preserved in the condensing silicate stardust. Likewise, C-giants (which evolve from M-giants

**Table 1: The stardust budget of the galaxy**

Source	contribution ( $10^{-6} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ )		
	carbon-dust	silicates	SiC
C-giants	2	--	0.07
M-giant	--	3	--
novae	0.3	0.03	[0.007]
planetary nebulae	0.04	--	--
Red Supergiants	--	0.2	--
WC stars	0.06	--	--
type II supernovae	[2]	[12]	--
type Ia supernovae	[0.3]	[2]	--

Ref.: [17], [18]

through the dredge up of freshly synthesized  $^{12}\text{C}$ ) will show a highly variable  $^{12}\text{C}/^{13}\text{C}$  ratio. Typically, these enrichments are a factor of a few, but much larger variations are possible. For example, stardust formed from the ashes of He-burning (ie., in type II SN or WC stars) consist exclusively of  $^{12}\text{C}$ . Contrariwise, C-soot formed in nova-ejecta is expected to have  $^{13}\text{C}/^{12}\text{C} > 1$ . Indeed, such isotopic variations have been the key in identifying interstellar dust components preserved in carbonaceous meteorites<sup>2</sup>.

While a large variety of objects contribute, the stardust budget is dominated by only a few (table 1)<sup>17,18</sup>. C-giants dominate the C-stardust injection. The He-burning shell in type II SN, containing mainly C and He, might contribute equally, provided mixing in the ejecta is unimportant. Otherwise,  $\text{C}/\text{O} < 1$  and no C-soot condensation is expected. The injection of elemental Si into the ISM is dominated by SN with some ( $\approx 20\%$ ) contribution by M-giants. However, although dust condensation has been observed in SN 1987a, no  $10\mu\text{m}$  silicate feature has been observed<sup>23</sup> (but large ( $>1\mu\text{m}$ ) silicates are not excluded). Its dust condensation efficiency is also poorly constrained ( $>0.01\%$ )<sup>24</sup>. Nevertheless, based upon the observed high depletion of Si from the gas phase, it is generally *assumed* that most of the Si enters the ISM in solid form and thus that SN dominate the silicate stardust budget. SiC stardust has only been observed around C-giants, but studies of meteorites suggest that novae might contribute as well<sup>2</sup>. In any case, the former is expected to dominate (table 1).

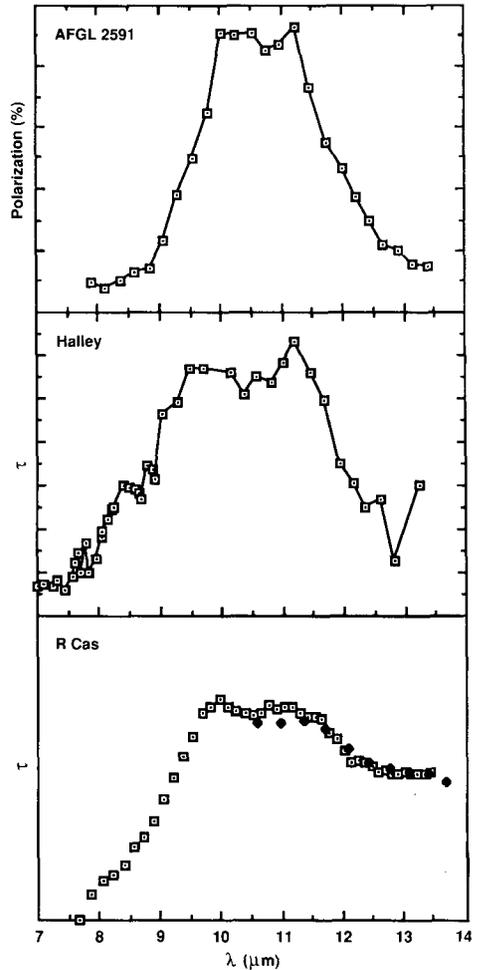
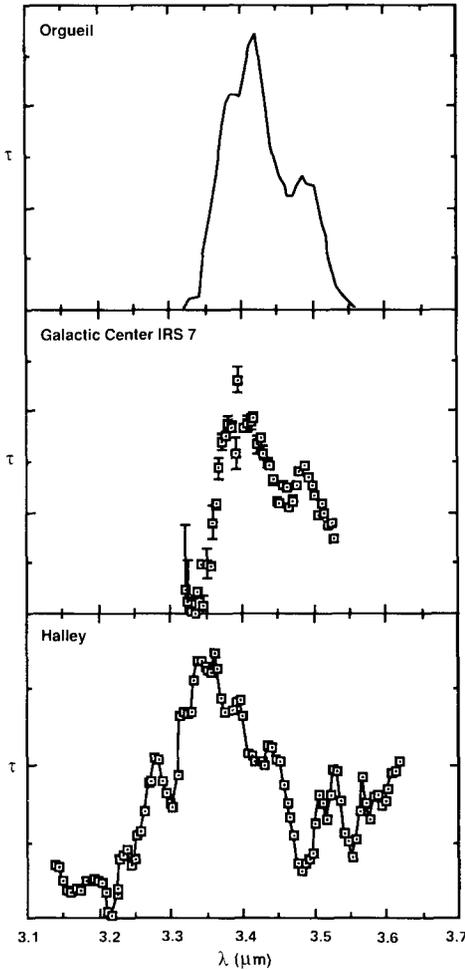


Fig. 4 (Left): The 3.4 $\mu$ m features observed in the acid-insoluble residue of the carbonaceous meteorite Orgueil, the galactic center source IRS 7, and comet Halley [3,24,30].

Fig. 5 (Right): The structure in the 10 $\mu$ m features observed in the protostar AFGL 2591, comet Halley, and the late type giant R Cas [20, 28, 29].

### 3 Interstellar Dust and Solar System Materials

It is of some interest to compare the observed properties of interstellar and circumstellar dust with those of solar system materials. A 3.4 $\mu$ m feature, characteristic for CH<sub>2</sub> & CH<sub>3</sub> stretching modes, has been detected in the ISM, in the acid-insoluble part of

carbonaceous meteorites, and in comet Halley (fig. 4). While the interstellar and meteoritic spectra show similar structure, the increased 3.38/3.42 ratio shows that the meteoritic hydrocarbons have  $\approx 20\%$  larger  $\text{CH}_2/\text{CH}_3$  ratio than in the ISM. The comet feature is distinctly different from the others, consisting of three components, at 3.28, 3.35, and  $3.52\mu\text{m}^{24}$ . These positions imply the presence of electronegative groups adjacent to the  $\text{CH}_2$  &  $\text{CH}_3$  groups. The first two features might be due to aromatic H and  $\text{CH}_2$  &  $\text{CH}_3$  groups on PAHs<sup>25</sup>, but HAC<sup>4</sup> is excluded. Their relative intensities imply then that  $\text{CH}_2$  &  $\text{CH}_3$  sidegroups are much more abundant in comets than on interstellar PAHs (cf., fig. 3). In this model, the  $3.52\mu\text{m}$  feature might originate in CC overtones of PAHs<sup>26</sup>. Alternatively, all three bands might have an origin in  $\text{CH}_2$  &  $\text{CH}_3$  groups connected to various unsaturated aliphatic (rather than aromatic) hydrocarbons<sup>27</sup>. In particular, the dominant  $3.35\mu\text{m}$  feature is very characteristic for such groups adjacent to C=O groups (ie, ketones and esters but not aldehydes). If these cometary hydrocarbon grains are related to the CHON particles detected by Giotto<sup>19</sup>, then the latter identification is perhaps more likely. In any case, it is discomfoting that the meteoritic hydrocarbon component, which has certainly been further processed on planetary bodies, resembles the interstellar  $3.4\mu\text{m}$  feature so well while the "pristine" cometary component is distinctly different.

While  $10\mu\text{m}$  cometary spectra show evidence for crystalline silicates<sup>28</sup>, the broad and structureless interstellar  $10\mu\text{m}$  feature is generally taken to imply an amorphous carrier. However, this might also be caused by a mixture of crystalline materials. Supporting this, some M-giants show a weak  $11.2\mu\text{m}$  feature (Fig. 5), probably due to crystalline olivine. Likewise, a  $10\mu\text{m}$  polarization study of a protostar reveals the presence of crystalline olivine in the ISM, although there is hardly a trace of it in absorption (fig 5)<sup>29</sup>.

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