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INFRARED SPECTROSCOPY OF ORGANIC MATERIAL IN DIFFUSE INTERSTELLAR CLOUDS

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ABSTRACT Spectra of objects which lie along several lines of sight through the diffuse interstellar medium (ISM) all contain an absorption feature near 3.4 μm which has been attributed to saturated aliphatic hydrocarbons on interstellar grains. The similarity of the absorption bands near 3.4 μm (2950 cm^{-1}) along different lines of sight reveal that the carrier of this band lies in the diffuse dust. Several materials have been proposed as "fits" to the 3.4 μm feature over the years. A comparison of these identifications is presented. A remarkable similarity between the spectrum of the diffuse dust and an organic extract from the Murchison meteorite suggests that some of the interstellar organic material may be preserved in primitive solar system bodies. The optical depth/extinction τ/A_V ratio for the 3.4 μm (2950 cm^{-1}) band is higher toward the Galactic center than toward sources which sample the interstellar medium in the local neighborhood. A similar trend has been observed previously for silicates, indicating that the two materials may be simultaneously enhanced in the Galactic center.

INTRODUCTION

Infrared spectral studies provide insight into the chemical identity of the organic component of the interstellar medium because the fundamental vibrational frequencies of the common chemical bonds between the most chemically abundant elements occur in the mid-infrared (5000 – 400 cm^{-1}; 2 – 25 μm). Infrared spectroscopic techniques have been used to detect organic material in the interstellar medium (Wickramasinghe & Allen 1980, 1983; Adamson, Whittet, & Duley 1990; Butchart et al. 1986; Sandford et al. 1991; Pendleton 1993) as well as in primitive solar system bodies such as comets, meteorites, and asteroids (Tokunaga & Brooke 1990; Cronin and Pizzarello 1990; Brooke, Tokunaga, & Knacke 1991; Cruikshank & Brown 1987; Ehrenfreund et al. 1991; Mueller et al. 1992).

Unequivocal identification of the specific molecules responsible for absorption and/or emission features observed in the ISM has met with limited success, in part due to technical constraints on the quality and completeness of astronom-

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ical spectra. Until fairly recently, adequate wavelength coverage at sufficiently high resolution and good signal-to-noise ratios were not available to distinguish between possible "fits" to the 3.4 μm feature. Consequently, the existing data through the CH region were "fit" with a variety of organic material, including E-Coli bacteria (Hoyle & Wickramasinghe 1982), organic grain mantles (Greenberg 1982; Schutte & Greenberg 1988), and Hydrogenated Amorphous Carbon (HAC) (Jones, Duley, & Williams 1987). Through comparisons of these materials to the higher resolution, high signal-to-noise data available today, it has become apparent that some of the proposed "fits" are not as similar to the diffuse dust spectra as had been assumed.

Over the years the instrumentation has improved dramatically, so that we are now able to see structure previously hidden in the 3.4 μm region. The 3.4 μm absorption band is actually composed of several bands which correspond to the stretching modes of C-H in saturated aliphatic hydrocarbons (Sandford et al. 1991; Pendleton 1993). Through a combined effort of infrared observational and laboratory analyses, the profile of the interstellar feature, as seen in the higher S/N data of Sandford et al. 1991, has been shown to be better fit by the spectra of residues produced through laboratory experiments which simulate chemical processing in the ISM than by other suggested materials, including HAC (see figures 1a and b). The organic extract of the Murchison meteorite (deVries et al. 1992) and the diffuse ISM (Figure 1a) reveals a striking similarity between the two. This was pointed out by Ehrenfreund et al. (1991) and Pendleton (1993). The similarity of the spectra suggest that some of the interstellar organic material may have been preserved in the carbonaceous meteorites. Comparisons to the Orgueil meteorite (Ehrenfreund et al. 1991) also show a strong similarity to the Galactic center data in the 3.4 μm region.

EVIDENCE FOR ORGANICS IN THE DIFFUSE DUST

The Galactic center

Until fairly recently, the only clear detection of the 3.4 μm absorption feature was along a line of sight toward the Galactic center (Butchart et al. 1986 and others). Two absorption bands are seen in the spectra of Galactic center sources (IRS 3, 6, & 7), the broad 3.0 μm feature is attributed to OH molecules and the 3.4 μm feature is attributed to the stretching vibration of the CH molecule. The CH feature does not vary from source to source, suggesting that the CH feature arises from dust in the diffuse ISM (MacFadzean et al. 1990; Sandford et al. 1991; Pendleton 1993). The OH feature is attributed to the presence of a molecular cloud which is fairly local to the Galactic center. The Galactic center sources are seen through varying amounts of the edge of the molecular cloud.

Figure 2a shows the 3.4 μm band seen toward the Galactic center source IRS6. The higher resolution spectra of the Galactic center sources [IRS7 (Sandford et al. 1991) and IRS6 (Pendleton et al. 1993)] show subfeatures at 3.38, 3.42, 3.48, and possibly 3.51 μm, which match the symmetric and asymmetric C-H stretching frequencies of CH_3 (methyl) and $-CH_2$ (methylene) groups in saturated aliphatic hydrocarbons. The relative peak heights imply that the average CH_2/CH_3 ratio of interstellar hydrocarbon is 2.5 +/- 0.4. The diffuse medium probably contains short chains of hydrocarbons such as $-CH_2-CH_2-CH_3$.

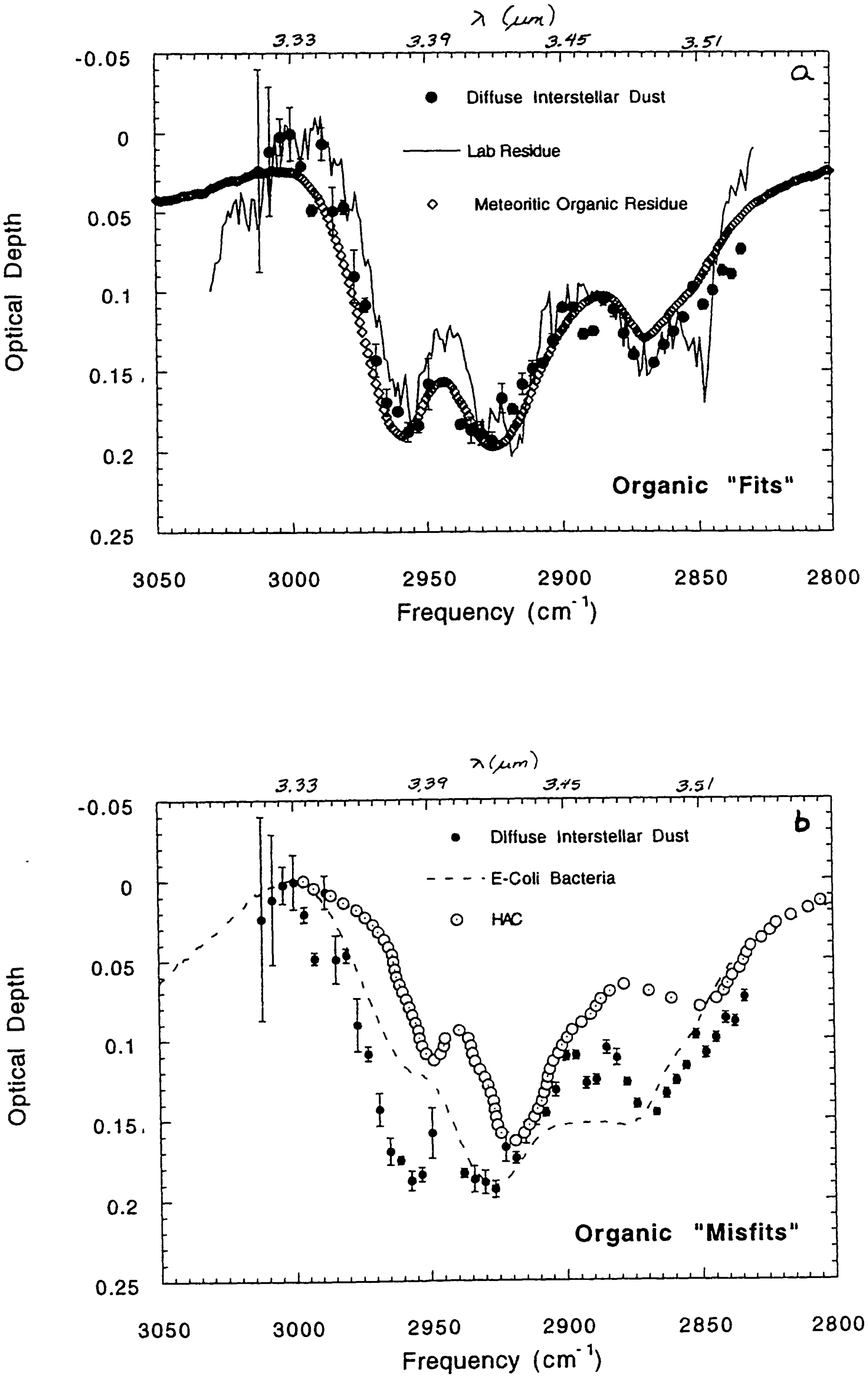

FIGURE 1 Infrared spectra of various materials that have been proposed as "fits" to the diffuse dust spectrum as seen toward the Galactic center source, IRS 7, (solid points) compared to a) lab residue produced through UV photolysis of an interstellar ice mixture that was then warmed to 200K (solid line), the near infrared spectrum of the acid insoluble organic extract from the Murchison meteorite (diamond symbol; deVries et al. 1992), b) Hydrogenated Amorphous Carbon (circles) and an infrared spectrum of E-Coli Bacteria (dashed line) taken at NASA Ames Research Center.

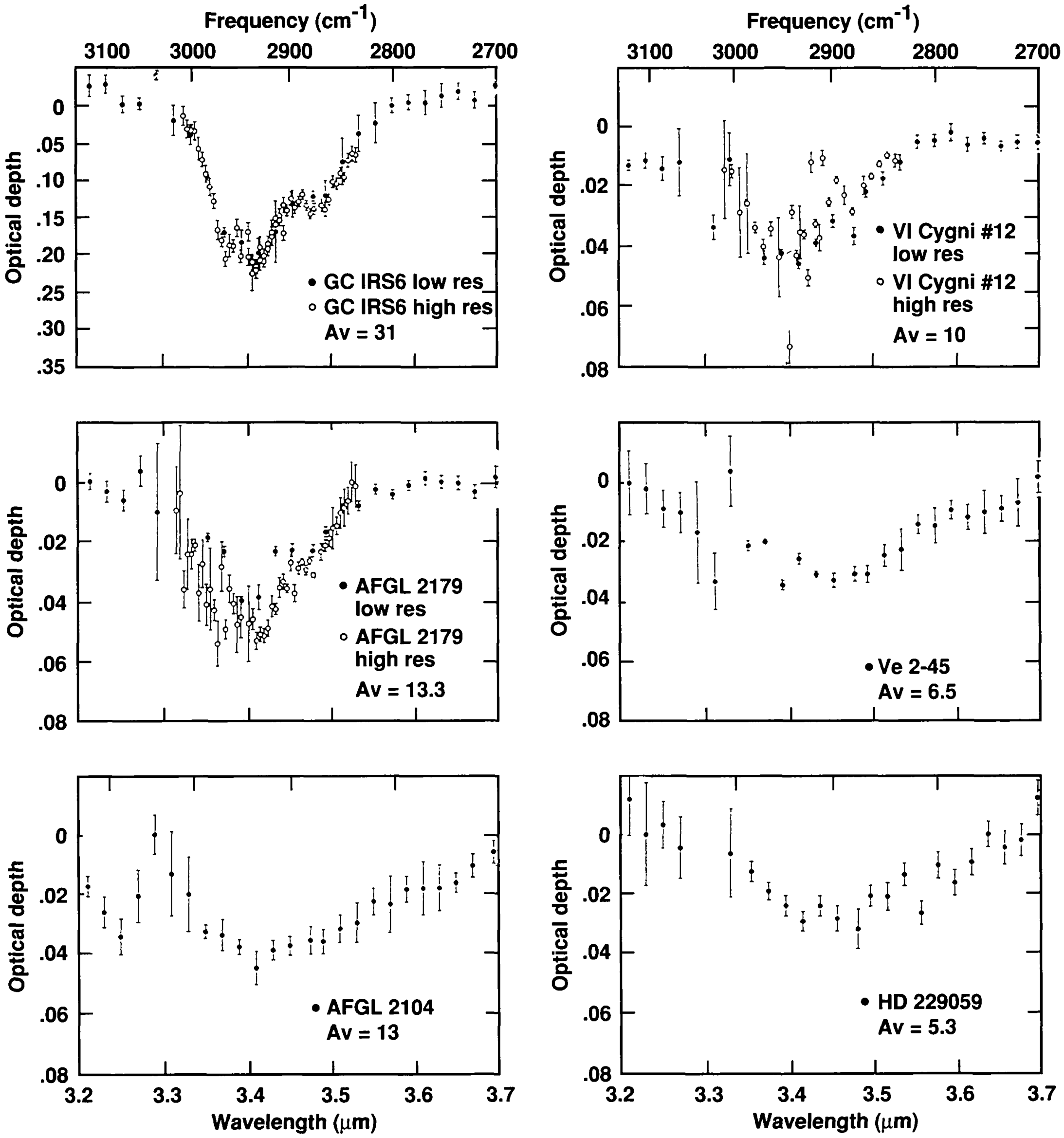

FIGURE 2 A comparison of optical depth plots for several different sightlines through our galaxy. The flux spectra that these plots were made from were obtained at the NASA IRTF using the 32 channel CGAS. The high resolution (R~700) data are superposed on the low resolution data (R~250). The figures (a-f) are ordered in terms of decreasing amounts of intervening extinction. The objects shown are: a) Galactic center source IRS 6 (A_V = 31), b) AFGL 2179 (A_V=13.3), c) AFGL 2104 (A_V=13), d) VI Cygni #12 (A_V=10, e) Ve 2-45 (A_V=6.5), and f) HD 229059 (A_V=5.3).

Other Sightlines Through the Galaxy

Adamson, Whittet, & Duley (1990) and Sandford et al. (1991) detected the 3.4 μm feature a line of sight away from the Galactic center toward the luminous supergiant, VI Cygni $^{\#}$12. These observations supported the assertion that the carrier resides in the diffuse medium. The observations shown in Figure 2 and others shown in Sandford et al. 1991, show that the feature appears along several different lines of sight toward objects which suffer varying amounts of interstellar extinction.

Figure 2 indicates the presence of the feature even in objects which suffer only small amounts of visual extinction. In order to be a good candidate for this type of project, the background "candle" object must not have interfering bands originating from the stellar photosphere. The objects used in this study (Pendleton et al. 1993) were primarily WC stars which have little H in their photospheres and therefore a CH band seen towards these objects likely arises from intervening material. The objects were also carefully selected so that they were not obscured by dense molecular cloud material, although some of the objects are still in the vicinity of the remnant parental cloud material. The absence of a strong OH feature at 3.0 μm provides a good indication that the line of sight does not intercept dense cloud material.

DUST IN THE DENSE AND DIFFUSE MEDIA

Ice mantles are observed in clouds with densities greater than $n_H \sim 10^4$ cm^{-3} (Whittet et al. 1988). As a production mechanism for solid carbon, UV photolysis of interstellar ice mantles in dense clouds is an important source of solid organic material in the diffuse ISM, since this process is efficient enough to surpass the output from AGB stars (Jenniskens et al. 1993). The evolution of organic refractory mantles has been discussed by several authors (Greenberg 1982; Moore & Donn 1982; Strazzulla et al. 1983; Tielens & Allamandola 1987; Schutte 1988). The schematic representation shown in Figure 3 (Pendleton & Cruikshank 1993) illustrates a possible scenario for the cycling of dust between the dense and the diffuse media. Figure 3 shows that with time, the simple ice mantle on a grain undergoes ultraviolet and/or thermal processing from nearby protostars. Upon cloud fragmentation and dissipation, the complex mantles are further heated which causes the volatile material to evaporate. The organic refractory material remains, and becomes incorporated into the diffuse medium. Further processing of the organic refractory grains by UV photons increases the refractory nature of the material as functional groups are removed (Jenniskens et al. 1993). Material from evolved stars mixes with the left over dense cloud material, and a new generation of dense clouds form out of the processed material. Note that the dense cloud scenario is completely analogous to the laboratory astrophysics experiments which produce the organic residue shown in Figure 1a. Infrared spectra of mixtures of molecular interstellar ice analogs reproduce many of the major spectral features attributed to ice in dense clouds (Tielens & Allamandola 1987; Allamandola & Sandford 1988; Allamandola, Sandford & Valero 1988). UV photolysis of such simple molecules produces new species, including radicals, within the ice. Upon heating, these chemically active species become free to move and react to form more complex compounds. Warming to

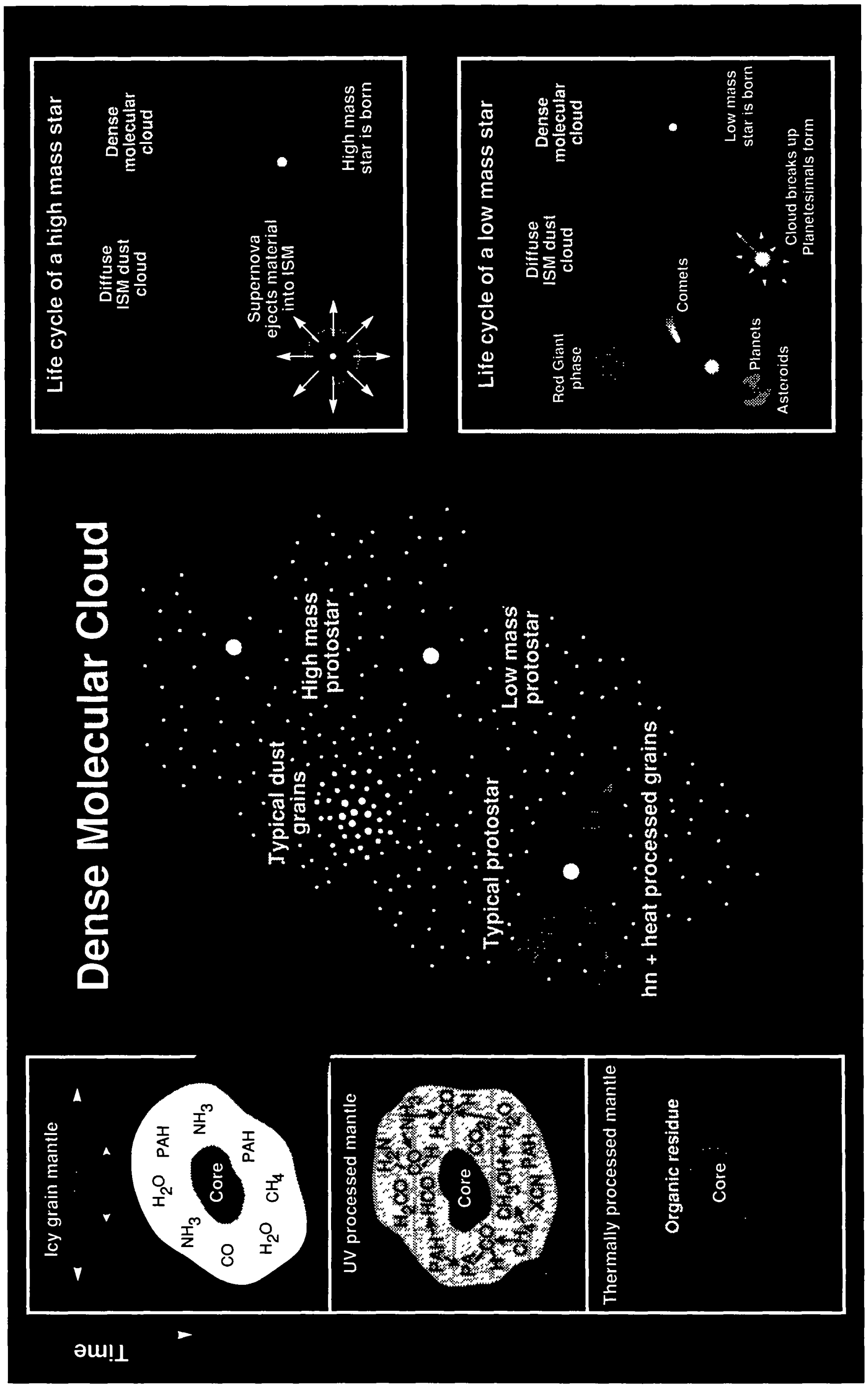

FIGURE 3 A schematic representation of the evolution of dust grains within a dense molecular cloud, and the subsequent enrichment of the diffuse interstellar medium by grains from evolved stars and dissipated molecular cloud material (Pendleton & Cruikshank 1993).

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200K leads to the evaporation of the original volatile ices. The remaining residue has a 3 μm infrared spectrum which closely matches the Galactic center source spectra. Therefore, the match shown in Figure 1a supports a model in which the diffuse medium hydrocarbon component contains a mixture of interlinked, aliphatic hydrocarbons which were produced by UV photolysis of interstellar ices.

A puzzling aspect to this scheme, however, is that the organic refractory component does not appear in the spectra of dense cloud sources. Given the relatively short cycling times between the dense and the diffuse clouds (McKee 1989), and the strength of the CH feature, the absence of the aliphatic component in the dense cloud spectra is surprising. Allamandola et al. (1993) reported the detection of a 3.47 μm (2880 cm^{-1}) absorption band in several protostellar sources which they attribute to interstellar diamond-like material. The diffuse medium aliphatic hydrocarbons are rich in methyl ($-CH_3$) and methylene ($-CH_2-$) groups which fall shortward and longward of this band, respectively, and they are not seen in the spectra of the embedded protostellar sources. Allamandola et al. (1993) point out that the absence of the $-CH_3$ and $-CH_2-$ bands in the dense cloud sources implies that C-rich materials in the diffuse medium do not become incorporated into, or do not survive incorporation into, dense molecular clouds. Smith, Sellgren, & Brooke (1993) have obtained spectra of dense cloud sources (and background field stars) for the Taurus cloud. Some of their low resolution observations show a 3.4 μm wing on the strong 3.1 μm water ice band. As expected from the higher resolution Allamandola et al. (1993) results for similar objects, the 3.4 μm wing does not show the substructure seen in the organic component of the diffuse medium. The Smith, Sellgren, & Brooke (1993) study also demonstrates that the 3.4 μm wing has the same A_V threshold as the 3.1 μm ice band, which is surprising if the wing were due to the hardier organic refractory material since the organic material should remain longer than the more volatile water ice component. Higher resolution data and a complete survey of both dense clouds and the diffuse medium are needed to better understand the evolution of dust from one regime to the other.

BAND DEPTH TO EXTINCTION RATIO

The τ/A_V relationship for the hydrocarbon feature is higher toward the Galactic center than toward sources in the local interstellar neighborhood. Figure 4 demonstrates the similarity of this trend with that of the τ/A_V relationship for the 9.7 μm silicate absorption band Roche & Aitken (1984; 1985). A paucity of carbon stars at the Galactic center has been suggested as an explanation for the enhanced silicate abundance (Roche 1988). However, the increasing $\tau_{3.4\mu m}/A_V$ towards the Galactic center may not be consistent with such an explanation. The fact that both materials track each other so well in abundance and the apparent increase of both materials in the Galactic center suggests that grains composed of both silicate cores and organic refractory mantles may be enhanced in the Galactic center. A very recent detection of the 3.4 μm absorption feature toward the nucleus of the Seyfert galaxy NGC 1068 (Bridger, Wright, & Geballe 1993) is the first extragalactic detection of the hydrocarbon feature. Preliminary results suggest that the ratio of $\tau_{3.4\mu m}/\tau_{9.7\mu m}$ for our galaxy (0.06; Adamson et

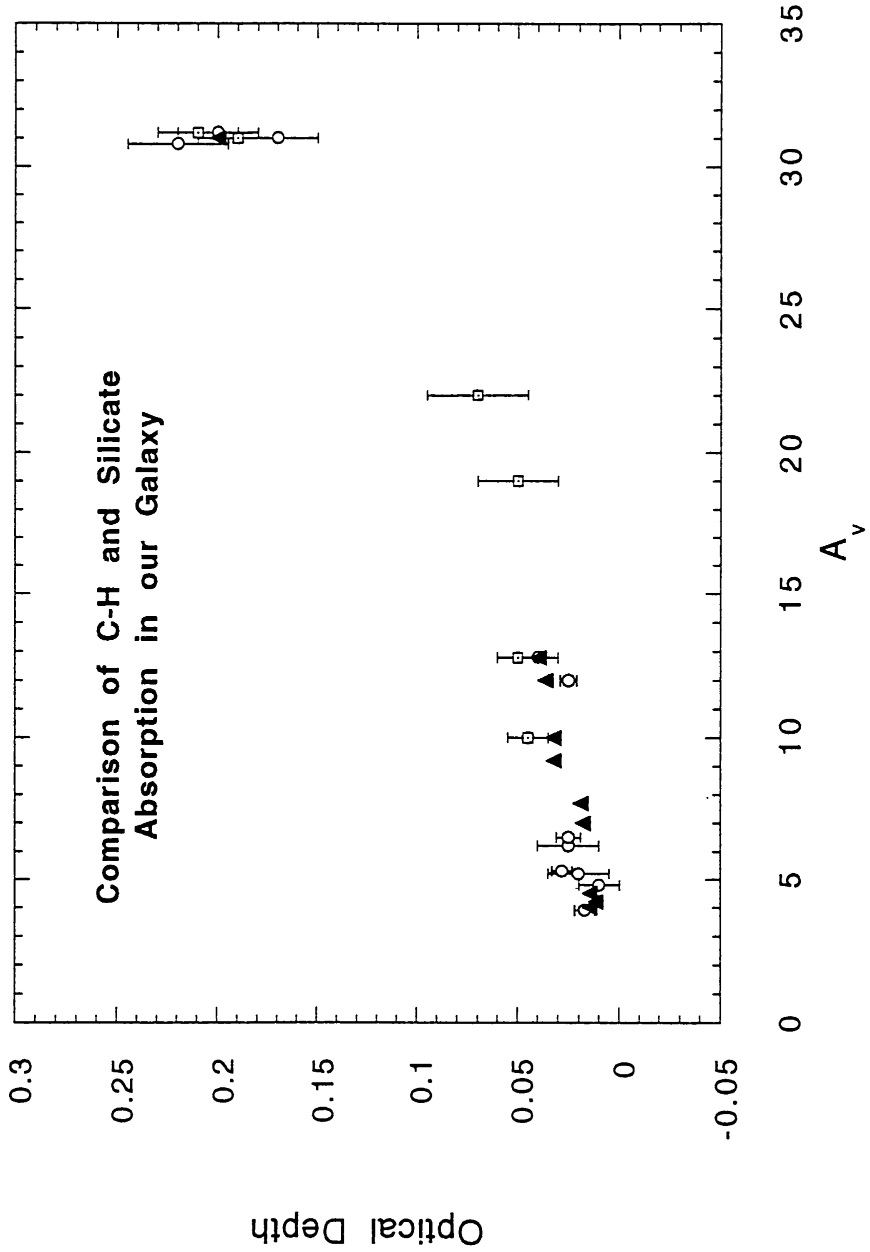

FIGURE 4 Comparison of the optical depth versus extinction data for the hydrocarbon and silicate absorption features. The high A_V sources are all at the Galactic center. The silicate feature optical depth data shown by the filled triangles (Roche & Aitken 1984), was divided by 18 for comparison with the hydrocarbon feature. Low resolution (R=250) and high resolution (R=700) hydrocarbon feature optical depth data (Pendleton et al. 1993) are indicated by open circles and squares, respectively.

al. 1990) is significantly different from that found for NGC 1068 (about 0.16; Bridger, Wright, & Geballe, 1993) which might indicate a higher fraction of organic to silicate dust in the dense torus around the nucleus of NGC 1068. A survey of the relative abundances of these materials in other spiral galaxies may aid in the understanding of the composition of our own galaxy.

An increase in grain size in the Galactic center might account for the enhanced C-H and silicate abundances. Lequeux & Jourdain de Muizon (1990) have detected the C-H (3.4 μm) and SiC (12 μm) bands in the circumstellar (carbonaceous) envelope of a proto- planetary nebula, CRL 618. The ratio of band depth to extinction is smaller in CRL 618 than toward the Galactic center, which they attribute to a lesser degree of hydrogenation of the material. Observations of objects with intermediate A_V values (15-20) would be extremely useful as a probe to the conditions which give rise to this interesting trend.

CONCLUSIONS

The carrier of the 3.4 μm band resides in the diffuse interstellar medium, as evidenced by the presence of the absorption feature along many lines of sight toward a variety of background candles. Higher resolution, higher signal-to-noise data has provided a new level of detail which shows that the 3.4 μm band is actually a combination of several C-H stretching bands. Due to the higher quality data, materials that were previously suggested as fits to the 3.4 μm feature have not proven to be well matched to the diffuse medium dust. Laboratory residues produced through the ultraviolet photolysis of simple interstellar ices and the organic insoluble extract from the Murchison meteorite provide a better fit to the diffuse dust than hydrogenated amorphous carbon material. A remarkable similarity exists between the high resolution diffuse dust spectra and the organic extract from the Murchison meteorite. The correlation between optical depth and A_V for both the hydrocarbon (3.4 μm) and silicate (9.7 μm) absorption features indicates that the two materials may be enhanced in the Galactic center.

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