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Spectroscopy of Hydrocarbon Grains toward the Galactic Center and Quintuplet Cluster

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Abstract. Our view of the Galactic center (GC) is affected by extinction from both diffuse interstellar medium (ISM) dust and dense molecular clouds along the line of sight. The enormous visual extinction present toward the center of our Galaxy ($\sim$ 31 magnitudes) necessitates a study of the interstellar dust properties as well as an investigation into the distribution of the different dust components. We have built upon the historic spectroscopy of Willner et al. (1979), Butchart et al. (1986), and McFadzean et al. (1989) in order to investigate the distribution of these dust components across the GC field. Specifically, we employ spectroscopy in the 3 μm region to investigate absorption features at 3.0 μm and 3.4 μm in lines of sight toward the GC central cluster and the Quintuplet cluster to the northeast. The 3.4 μm feature is one of the primary spectral signatures of the organic component of interstellar dust and is, to date, only observed in the cold diffuse interstellar medium. The 3.0 μm ice feature is carried by dense molecular cloud material, and can therefore be used to loosely trace the distribution of such material across the GC field. By obtaining spectra for multiple sightlines we have been able to deconvolve the diffuse ISM and dense molecular cloud components. Our study shows that differences exist in the spectra of relatively nearby lines of sight in the Galactic center central cluster. The depth of the 3.0 μm water-ice feature varies by a factor of almost 5 across a 2 parsec (in projection) region, perhaps reflecting the clumpy nature of the dense clouds. In addition, we found that the 3.4 μm hydrocarbon feature varies in depth across the areas studied toward the central cluster, whereas the depth is relatively constant toward the Quintuplet cluster. This is likely a reflection of the distribution of extinction from the foreground diffuse ISM.

Our ground-based and space-based spectroscopy reveals differences in absorption features in the 3 and 6 μm regions between sightlines toward the GC central cluster and those toward the Quintuplet cluster. While the 3 μm spectra of both regions show a broad absorption feature blueward of the 3.4 μm absorption, only the Quintuplet spectra show a distinct absorption feature at 3.28 μm. This feature is indicative of the presence of polycyclic aromatic hydrocarbons (PAHs) along the line of sight. The Quintuplet-proper sources have 6 μm spectra that are markedly different than that of GC IRS 7 in the central cluster, and instead strongly resemble the spectra seen toward dusty late-type carbon-class (WC) Wolf-Rayet stars. This is the first hint of some spectroscopic similarity between the Quintuplet sources and dusty WC stars.

1 Introduction

The center of our Galaxy is obscured by some 30 magnitudes of visual extinction. Investigations of objects located near the Galactic center (GC) require an understanding of the physical properties of the intervening dust through which all observations are made. Some of the dust is local to the GC, while much of it lies along the line of sight. Bright infrared sources located at the GC are used to probe this dust. The line of sight toward the GC is dominated by diffuse ISM dust (Lebofsky 1979), however it was suggested by

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McFadzean et al. (1989) that there is a molecular cloud component that contributes to the extinction toward the GC. Space-based spectroscopy with the Infrared Space Observatory (ISO) confirmed the presence of molecular cloud material by revealing absorption due to icy grain mantles (de Graauw et al. 1996; Lutz et al. 1996; Gerakines et al. 1999). It has been estimated that as much as one-third of the visual extinction arises in molecular cloud material (Whittet et al. 1997). Much of the molecular cloud extinction presumably arises in dust clouds located within 4 kpc of Earth (Sanders, Scoville & Solomon 1985). If this is so, then the clouds are not associated with the infrared sources that provide the continuum against which molecular absorption features can be observed.

The diffuse interstellar medium is devoid of ices and instead contains only the refractory grain component, which includes aromatic (ring-like) and aliphatic (chain-like) hydrocarbons and silicates (Figs. 1 and 4). Hydrocarbons in the form of aromatics and aliphatics are a significant component of the diffuse ISM (e.g., Pendleton & Allamandola 2002). Aromatic hydrocarbons, observed throughout our Galaxy and other galaxies, are characterized by a family of bands normally observed in emission around 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm (Allamandola, Tielens, & Barker 1989). Short-chained aliphatic hydrocarbons (Fig. 4, rightmost insert) are characterized by absorption at 3.4 μm and subfeatures due to CH_2 (methylene) and CH_3 (methyl) stretching modes at 3.38 and 3.48 μm (methylene) and 3.42 μm (methyl) (Sandford et al. 1991). Their spectral signature is seen not only toward the GC (Butchart et al. 1986), but in diffuse ISM dust throughout our Galaxy (Pendleton et al. 1994) and other galaxies (Wright et al. 1996). The 3.4 μm absorption feature observed in the diffuse ISM is distinct from that seen in dense molecular clouds (Brooke et al. 1996; Chiar et al. 1996). The latter is a smooth feature centered at 3.47 μm and the carrier is thought to coexist with H_2O-ice in the grain mantle. In contrast, the diffuse ISM hydrocarbons are most likely carried by a population of very small unaligned grains, rather than refractory mantles on silicate cores (Chiar et al. 1998; Adamson et al. 1999; Ishii et al. 2002), although the interpretation of these results remains controversial (Li & Greenberg 2002).

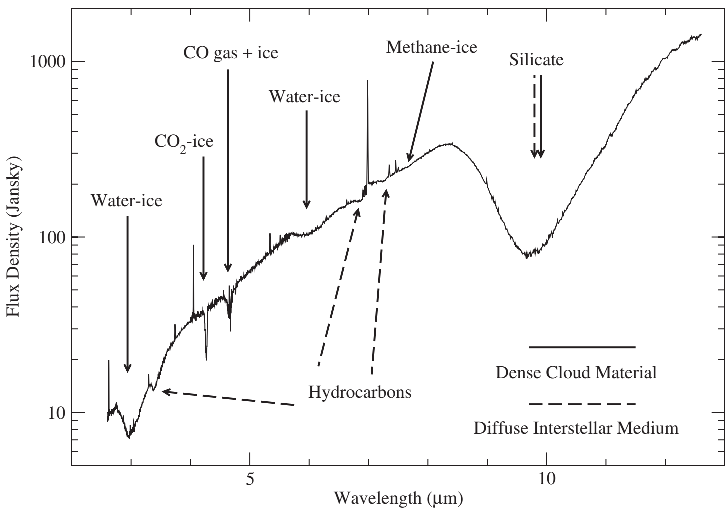

Fig. 1 ISO-SWS spectrum centered on GC IRS 7. The beam size was $14'' \times 20''$. Absorption features arising in the diffuse ISM and dense molecular cloud material are noted. Figure adapted from Lutz et al. 1996 and Chiar et al. 2000.

2 Dense Cloud Absorption Features

Ices in the cold molecular cloud material along the GC line of sight are characterized by absorption features due to H_2O (3.0, 6.0 μm), CO_2 (4.27 and 15.3 μm), and CH_4 (7.67 μm) (Chiar et al. 2000; Gerakines et al. 1999; de Graauw et al. 1996; Lutz et al. 1996). The Short-Wavelength Spectrometer (SWS) on ISO

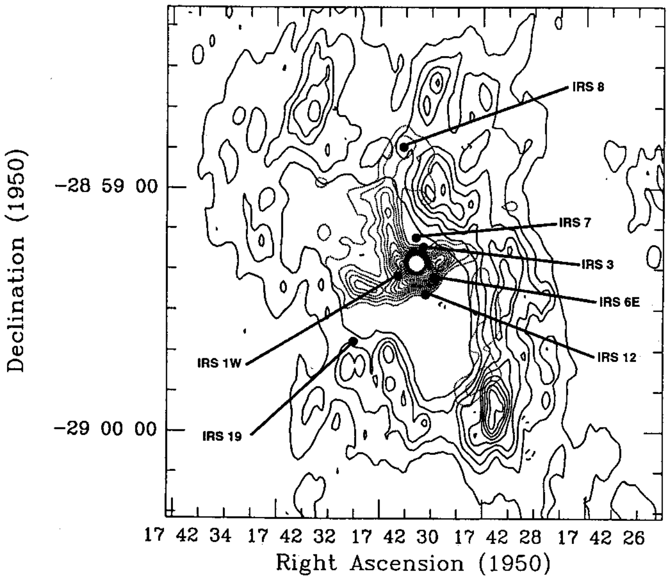

Fig. 2 Positions of infrared sources overlaid on a map of HCN J=1-0 emission (solid contours) and ionized gas at 15 GHz (dotted contours) [Reproduced from Güsten et al. 1987.]. HCN emission traces the high density molecular gas in the circumnuclear ring. Contour interval for the velocity-integrated HCN emission is 0.15 K averaged over 300 km s^{-1} in a $2''$ beam. Dotted contours of 15 GHz emission at 20 K intervals in a $3.6'' \times 3.4''$ beam. The radio-source Sgr A* is located at $\alpha = 17^{h}42^{m}29.2^{s}$ $\delta = -28°59'19''$. The GC Quintuplet sources are located $14'$ northeast of the GC, $\sim$ 30 pc away (assuming a distance of 8.5 kpc)

observed the line of sight toward GC IRS 7 with a $14'' \times 20''$ beam. The spectrum from 2.6 to 12.5 μm is shown in Fig 1. Absorption features due to solid CO_2 and CH_4 are present; analysis of the profiles showed that the abundances of these molecules relative to H_2O-ice are similar to those observed in local molecular clouds (Boogert et al. 1998; Gerakines et al. 1999; Chiar et al. 2000). The 6.0 μm absorption feature has been previously studied with the Kuiper Airborne Observatory (using FOGS and HIFOGS; Willner et al. 1979; Tielens et al. 1996), then later by ISO-SWS (Chiar et al. 2000; Fig. 5). There is some controversy surrounding the precise identification of the 6 μm profile, although it is generally accepted that it can at least be partially attributed to H_2O-ice with possible trace amounts of other ices (Chiar et al. 2000). A comparison between the 6 μm absorption profile observed toward GC IRS 7 and the Quintuplet-proper sources is shown in Fig. 5 and discussed in section 4.

While airborne and space-based observations enabled us to study the average ice properties along the line of sight, spatial information could not be ascertained. The ISO-SWS observations, centered on GC IRS 7, were made with a large beam and included the sources GC IRS 1, IRS 3, much of the ionized bar and the ionized northern arm (Lutz et al. 1996). The KAO observations were carried out with a similarly large beam with FOGS and HIFOGS centered on GC IRS 3 (Tielens et al. 1996). In order to gain insight into the distribution of diffuse ISM dust and dense cloud material, we undertook a program of 3 μm spectroscopy of the positions shown in Fig. 2 (Chiar et al. 2002) at the United Kingdom Infrared Telescope (UKIRT) using the the $0.6''$ slit of the Cooled Grating Spectrometer, CGS4. The 3 μm region includes absorption features due to H_2O-ice and aliphatic and aromatic hydrocarbons. Aliphatic hydrocarbons reside in the diffuse ISM and are discussed further below. Water-ice is the most abundant mantle constituent in any dense cloud, so we use it to trace the dense cloud material.

Our spectroscopy shows that the H_2O-ice profile shape is remarkably consistent across the seven lines of sight studied, including GC IRS 8 and IRS 19, which are located apart from the central cluster, closer to the GC circumnuclear ring (Fig. 2; Geballe et al. 1989). Compared to local molecular cloud ice profiles, e.g., in Taurus, the GC profile is broader and peaks at shorter wavelengths (Fig. 3). Laboratory spectra of pure H_2O-ice are not able to account for the observed absorption in the GC ice profile; additional absorption is present shortward of 3 μm and from 3.2 to 3.6 μm (in addition to the 3.4 μm hydrocarbon feature). The possibility that the blue excess is due to NH_3-ice has been discussed by Chiar et al. (2000), although other explanations may be plausible (Dartois & d'Hendecourt 2001). We find that the optical depth of the ice band is the greatest toward GC IRS 19 ($\tau_{3.0} = 1.5$), a factor of almost 5 greater than the weakest ice band (Chiar et al. 2002). The variation of the 3.0 μm profile depth across the central GC field has been noted previously by McFadzean et al. (1989).

We also obtained a 4.5–5 μm spectrum of the line of sight toward GC IRS 19, to search for evidence of solid CO absorption, since it has the deepest H_2O-ice band (and therefore a high abundance of icy grain mantles). In addition to unresolved gas-phase CO lines, our spectrum shows a weak solid CO feature at 4.67 μm and an X-C≡N feature at 4.62 μm (Chiar et al. 2002). The solid CO to H_2O-ice ratio is similar to that observed in local molecular clouds. In the solar neighborhood, the X-C≡N feature is seen only toward some deeply embedded protostars. Toward the GC, it may indicate the serendipitous presence of such an object in the line of sight to IRS 19, or it might conceivably arise from the processing of ices in the circumnuclear ring of the GC itself.

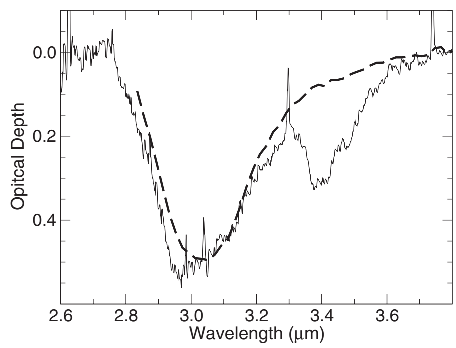

Fig. 3 Comparison of the 3 μm ice feature observed in the local Taurus molecular cloud (toward the background star, Elias 16; Smith et al. 1993; dashed line) and in the molecular clouds along the line of sight toward the Galactic center (ISO-SWS spectrum from Chiar et al. 2000; solid line). The absorption feature centered at 3.4 μm in the GC spectrum is indicative of aliphatic hydrocarbons in the diffuse ISM (see text).

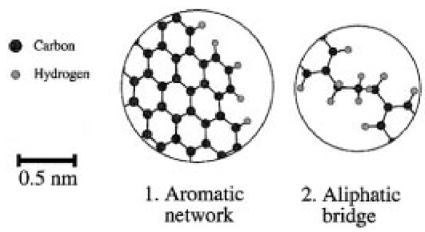

Fig. 4 The two classes of hydrocarbons thought to be present in the diffuse interstellar medium. Aliphatic (chain-like) hydrocarbons exhibit C-H stretching vibration modes near 3.4 μm, whereas the C-H stretching vibration of aromatic (ring-like) hydrocarbons is centered near 3.3 μm. Adapted from Pendleton & Allamandola 2002

3 Diffuse Interstellar Medium Absorption Features

The structured 3.4 μm absorption feature (e.g., Fig. 5, left panels) has been the focus of many laboratory investigations into the exact nature of the hydrocarbon material (see Pendleton & Allamandola 2002 for a review). While many laboratory analog materials have provided insight into the carrier of the interstellar band based on absorption signatures at 3.4 μm, longer wavelength spectroscopy obtained from space using ISO's SWS revealed vital information regarding the corresponding deformation modes at 6.85 and 7.25 μm toward the GC (Chiar et al. 2000). The relative strengths of these three features (Chiar et al. 2000), along with a detailed analysis of laboratory data produced via competing processes, have revealed that hydrogenated amorphous carbon produced through plasma processing, closely matches the interstellar data (Pendleton & Allamandola 2002).

Our UKIRT-CGS4 spectroscopy of the GC central cluster sources, described in section 2, shows that the depth of the aliphatic hydrocarbon absorption at 3.4 μm varies by a factor of 1.7, indicating significant changes in the foreground extinction across the small field. Our spectroscopy of multiple sightlines allowed for deconvolution of the diffuse ISM absorption from the dense cloud absorption component (Chiar et al. 2002). Many previous studies of the 3.4 μm feature relied on fitting a local continuum over the 3.3 to 3.7 μm region. Our method helped us uncover broad absorption on the blue shoulder of the 3.4 μm absorption feature in the approximate spectral region where polycyclic aromatic hydrocarbons (PAHs; Fig. 4, left insert) are expected to absorb. The depth of the absorption does not correlate with the depth of the ice band, thus it is a characteristic of the diffuse ISM dust along the line of sight (Chiar et al. 2002). However, the width of the "feature" is too great to be simply reconciled with PAHs in solid grain material. The nature of this broad absorption is still an open question.

Our combined UKIRT-CGS4 and ISO-SWS spectroscopy in the 3 and 6 μm regions revealed significant differences between the spectra of the GC central sources and the Quintuplet sources (Fig. 5). For instance, in addition to the broad shoulder described above, a distinct narrow 3.28 μm absorption feature is present in the Quintuplet cluster spectra (Chiar et al., in preparation), but is (probably) absent in the spectra of the GC central cluster sources. The central wavelength and width of the absorption feature are indicative of the C-H stretching vibration in PAHs. Whether the carrier of the absorption is intrinsic to the Quintuplet cluster sources or a widespread diffuse ISM dust component is unclear. The 6 μm spectra of the Quintuplet-proper sources exhibit an absorption feature centered at 6.2 μm, markedly different than the symmetric absorption feature present in the GC IRS 7 spectrum. We discuss a possible explanation for these profile differences below.

4 The Enigmatic Quintuplet Sources

The five bright Quintuplet sources were discovered in near-IR surveys by Okuda et al. (1990) and Nagata et al. (1990). We will refer to these original sources as the Quintuplet-proper sources. The surrounding cluster was revealed by later surveys (e.g., Moneti et al. 1992), and most recently by the Hubble Space Telescope which revealed hundreds of sources (Figer et al. 1999). Some of these stars have been classified as Wolf-Rayet stars, Luminous Blue Variables and OB supergiants (Figer, McLean, & Morris 1999). However, the nature of the Quintuplet-proper sources remains uncertain due to non-detection of photospheric features which would enable their spectral classification. Each of the proposed identifications – massive dust-enshrouded young stars, OH-IR stars, dusty late-type carbon-class (WC) Wolf-Rayet stars – has its problems (Nagata et al. 1990; Figer, McLean, & Morris 1999; Moneti et al. 2001). We favor the dusty late-type WC star hypothesis. Figer, McLean, & Morris (1999) were the first to suggest that the Quintuplet sources may be dusty late-type WC stars. Moneti et al. (2001) analyze the spectral energy distributions (SEDs) of the Quintuplet sources and find that they are best reproduced by disk models similar to those used by Williams et al. (1987) to model SEDs of dusty late-type WC stars. However, the lack of the near-IR emission lines in the Quintuplet spectra normally used to classify the WC stars is problematic (Figer, McLean, & Morris 1999).

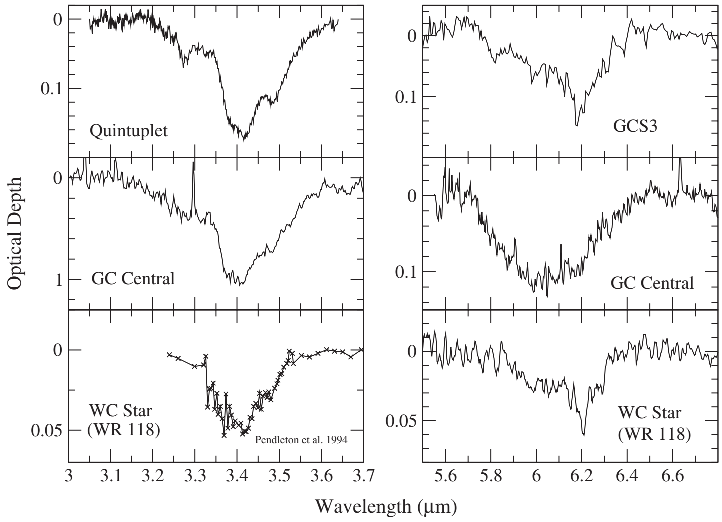

Fig. 5 The 3 and 6 μm spectral regions for the Quintuplet-proper members, the GC central cluster sources, and a dusty late-type carbon-class Wolf-Rayet star (WR 118). Spectra are from Chiar et al. 2003 (Quintuplet-proper, 3 μm; UKIRT-CGS4), Chiar et al. 2000 (Quintuplet (GCS3) and GC Central, 6 μm; ISO-SWS), Pendleton et al. 1994 (WR 118, 3 μm; Infrared Telescope Facility), Chiar & Tielens 2001 (WR 118, 6 μm; ISO-SWS), Chiar et al. 2002 (GC Central, 3 μm; UKIRT-CGS4). The 3 μm Quintuplet spectrum is an average of the individual spectra centered on each of Quintuplet-proper members. The GC Central 3 μm spectrum is an average of 5 spectra, each has been scaled to $\tau = 1.0$ near 3.4 μm. The 6 μm spectrum of GCS3 was centered on GCS3-I; the ISO-SWS beam included GCS 3-II and GCS3-III (partially).

Our 6 μm spectroscopy reveals a similarity between the Quintuplet proper sources and dusty WC stars (Fig. 5). A distinct 6.2 μm absorption feature is seen toward several dusty WC stars (Schutte et al. 1998; Chiar & Tielens 2001) and the Quintuplet proper sources. The absorption feature has been attributed to the C-C stretch in amorphous carbon in the hydrogen-deficient circumstellar material associated with the WC stars, rather than PAHs in the interstellar dust along the line of sight (Chiar & Tielens 2001). Fig. 5 displays the 6 μm spectra from ISO-SWS of the lines of sight toward the Quintuplet source GCS 3-I, GC IRS 7, and the WC star WR 118. We note that the 3.4 μm hydrocarbon feature observed toward WR 118 is carried by the 12 magnitudes of interstellar visual extinction along the line of sight, and is not circumstellar in nature. Due to the extreme hydrogen deficiency in the WC star circumstellar environment, it is not possible to form hydrocarbon material. A broad symmetric 6.0 μm absorption feature is seen in the GC IRS 7 spectrum; the absorption is mostly accounted for by ices in the dense cloud material along the line of sight. The similarity between the WC star spectra and the GCS 3 spectrum and the dissimilarity of the GC IRS 7 spectrum is striking. These spectra are the first hint of some spectroscopic similarity between the Quintuplet sources and any of the proposed classifications, and lends support to the suggestion that they are dusty WC stars.

5 Conclusions and Future Work

Our recent spectroscopy of lines of sight toward the GC central cluster and the Quintuplet cluster has given us great insight into the chemical composition, characteristic absorption profiles, and distribution of both the diffuse ISM and dense clouds components along the line of sight. In addition, our group has carried out a program of narrow-band imaging in order to fully map the variation of the ice, hydrocarbon, and silicate dust components toward the GC central cluster, including the circumnuclear ring (Adamson et al. 2003). Future spectroscopic observations from airborne (SOFIA) and ground-based observatories will answer such questions as 1. Do icy grain mantles in the circumnuclear ring contribute to the deep ice features and

X-C≡N feature observed in those lines of sight? 2. Is the 6 μm absorption profile of the Quintuplet-proper members unique to those sources and dusty late-type WC stars? 3. Is the distinct 3.28 μm feature observed in the Quintuplet-proper spectra due to PAH absorption in the diffuse ISM? 4. Will this feature be present in high signal-to-noise spectra of other diffuse ISM lines of sight such as heavily extincted WC stars? 5. Is this feature really absent in lines of sight toward the GC central cluster? The answers to questions 2 through 5 will not only tell us more about aromatic hydrocarbons in the diffuse ISM, but will also bring us closer to uncovering the nature of the enigmatic Quintuplet sources.

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