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# SPECTROPOLARIMETRY OF THE 3.4 μm FEATURE IN THE DIFFUSE ISM TOWARD THE GALACTIC CENTER QUINTUPLET CLUSTER

J. E. Chiar,[1] A. J. Adamson,[2] D. C. B. Whittet,[3] A. Chrysostomou,[4] J. H. Hough,[4] T. H. Kerr,[2] R. E. Mason,[5] P. F. Roche,[6] and G. Wright[7]

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## ABSTRACT

Aliphatic hydrocarbons exhibit an absorption feature at 3.4 μm, observed toward sources that sample diffuse regions of the interstellar medium (ISM). The absorbers responsible for this feature are assumed to reside in some component of interstellar dust, but the physical nature of the particles (size, shape, structure, etc.) is uncertain. Observations of interstellar polarization provide discrimination. Since the grains that carry the silicate absorption feature are known to be aligned, polarization across the 3.4 μm hydrocarbon feature can be used to test the silicate-core organic refractory mantle grain theory. Although the 3.4 μm feature has been observed to be devoid of polarization for one line of sight toward the Galactic center, a corresponding silicate polarization measurement for the same line of sight was not available. Here, we present spectropolarimetric observations of GCS 3-II and GCS 3-IV toward the Galactic center, where the 9.7 μm silicate polarization has been previously observed. We show that polarization is not detected across the 3.4 μm feature to a limit of 0.06% ± 0.13% (GCS 3-II) and 0.15% ± 0.31% (GCS 3-IV), well below the lowest available prediction of polarization on the basis of the core-mantle model. We conclude that the hydrocarbons in the diffuse ISM do not reside on the same grains as the silicates, and likely form a separate population of small grains.

*Subject headings:* dust, extinction — ISM: clouds — ISM: general — ISM: individual (GCS 3-II, GCS 3-IV) — ISM: lines and bands — ISM: molecules

## 1. INTRODUCTION

Dust grains in the diffuse interstellar medium (ISM) are composed of both oxygen-rich and carbon-rich material (e.g., Mathis 1996; Draine 2003). While the O-rich component is attributed to amorphous silicates, the composition of the C-rich component remains controversial, with proposed candidates including graphite, diamond, amorphous carbon, aromatic and aliphatic hydrocarbons, and organic refractory residues. Of these, aliphatic hydrocarbons are confirmed to be present in the interstellar media in our own and other galaxies, through observations of vibration absorption features centered at 3.4 μm (C—H stretch), 6.85, and 7.25 μm (deformation modes). In the Milky Way, hydrocarbons are detected along lines of sight that probe the local diffuse ISM within 3 kpc of the Sun (Adamson et al. 1990; Sandford et al. 1991; Pendleton et al. 1994; Whittet et al. 1997) and along the line of sight toward the Galactic center (GC; McFadzean et al. 1989; Sandford et al. 1991; Pendleton et al. 1994; Chiar et al. 2000, 2002). These same hydrocarbon features are also observed in dusty Seyfert and ultraluminous infrared galaxies (Imanishi 2000; Mason et al. 2004; Spoon et al. 2004; Imanishi et al. 2006). Within the profile of the 3.4 μm feature, the relative depths of subfeatures at 3.39, 3.42, and 3.49 μm are indicative of short-chained hydrocarbons, with other perturbing chemical groups (Sandford et al. 1991). Based on the depth of the corresponding deformation features at 6.85 and 7.25 μm, the best candidate material is likely to be hydrogenated amorphous carbon (HAC; Chiar et al. 2000; Pendleton & Allamandola 2002; Mennella et al. 2002).

Although these aliphatic hydrocarbons seem to be ubiquitous constituents of galactic interstellar media, and much has been learned about their molecular structure, their formation pathways and physical location within grain populations are still debated. Two production routes have been proposed. One postulates that organic refractory mantles (ORM) are formed in the diffuse ISM by UV processing of ice mantles originating in denser clouds (Greenberg 1989; Greenberg & Li 1996; Li & Greenberg 1997). Dust grains are, indeed, expected to cycle between dense and diffuse phases of the ISM, before being consumed by star formation (McKee 1989). Spectroscopically, carbonaceous materials produced in this manner provide a reasonable match to the 3.4 μm absorption feature, although they do not reproduce the observed deformation modes at longer wavelengths (see Pendleton & Allamandola 2002). This model predicts that the carrier of the 3.4 μm feature resides in a mantle on a silicate core. In the alternative scenario, production occurs in situ in the diffuse ISM, via hydrogen bombardment of preexisting carbon particles (e.g., Mennella et al. 2002). This model predicts hydrocarbons and silicates to be separate grain populations, at least in low-density environments where grain-grain coagulation is less important. This difference in physical location predicted for the absorber provides a means of discrimination.

Much can be learned about the physical properties of dust grains through polarimetric measurements of their solid-state absorption features. Excess polarization across a particular feature is a sign that the grains in which the absorber resides are aligned by the magnetic field. Furthermore, lack of excess polarization across a particular feature implies poorly aligned grains, or grains with optical properties, including shape, that induce little or no polarization. Note that the alignment efficiency is a

[1] SETI Institute, 515 North Whisman Drive, Mountain View, CA 94043; and NASA-Ames Research Center, Mail Stop 245-3, Moffett Field, CA 94035.

[2] Joint Astronomy Centre, 660 North A'ohoku Place, University Park, Hilo, HI 96720.

[3] Rensselaer Polytechnic Institute, Department of Physics, Applied Physics and Astronomy, Troy, NY 12180.

[4] Department of Physical Sciences, University of Hertfordshire, Hatfield, AL10 9AB, UK.

[5] Gemini Observatory, 670 North A'ohoku Place, University Park, Hilo, HI 96720.

[6] Department of Astrophysics, Oxford University, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK.

[7] UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK.

strong function of particle size (e.g., Draine 2003), with very small (<0.01 $\mu$m) grains being generally much less well aligned, compared with larger "classical" grains. The aligned grain population includes silicates, which exhibit excess polarization across the 9.7 and 18.5 $\mu$m absorption features in lines of sight that probe both the diffuse ISM and stars embedded in their nascent molecular clouds (e.g., Aitken et al. 1988, 1989; Smith et al. 2000; Wright et al. 2002). In dense molecular clouds where conditions are sufficiently cold for ice mantles to form, polarization excesses across the 3 $\mu$m $H_2O$-ice feature (e.g., Kobayashi et al. 1980; Hough et al. 1988; Holloway et al. 2002) and the solid-CO feature (Chrysostomou et al. 1996) are also detected, giving firm support for the existence of aligned grains that have silicate cores surrounded by ice mantles. It is reasonable to suppose that such grains will continue to produce polarization as they cycle into the diffuse ISM, where conditions are generally more conducive to efficient alignment (Lazarian et al. 1997), irrespective of modification to the mantles.

Since the silicate feature toward the GC is known to be polarized, a good test of the ORM theory is measurement of polarization across the 3.4 $\mu$m feature. If the hydrocarbons reside in mantles on silicate cores, then clearly the feature should be polarized at a similar level. Nagata et al. (1994) found no significant peak around 3.4 $\mu$m in their low-resolution spectropolarimetric data of several Galactic center sources (including GC-IRS7 and GCS 3-II). Higher resolution spectropolarimetric observations of GC-IRS7 were carried out by Adamson et al. (1999), who showed that the 3.4 $\mu$m feature in GC-IRS7 is not polarized. This challenged the ORM theory. However, interpretation of this result was complicated by the fact that the silicate polarization toward GC-IRS7 was inferred from a measurement toward the nearby line of sight, GC-IRS3. Although GC-IRS3 is located only $\sim 3''$ away from GC-IRS7, since the polarization toward GC-IRS7 was not measured directly, the possibility remains that mantled silicate grains along this line of sight either fail to align or produce no net polarization for some other reason (Li & Greenberg 2002). To remove this ambiguity, we have undertaken spectropolarimetry of the 3.4 $\mu$m hydrocarbon feature toward two lines of sight in the Quintuplet cluster, for which silicate spectropolarimetry already exists (Smith et al. 2000).

In § 2, we describe the observations and the data reduction methods used to produce the polarization spectra. In § 3, we discuss the available spectroscopic and polarimetric observations of the Quintuplet sources, and in § 4 we present the new spectropolarimetric data for the 3.4 $\mu$m feature. Finally, in § 5 we discuss the implications for grain models of the nondetection of 3.4 $\mu$m polarization.

## 2. OBSERVATIONS AND DATA REDUCTION

Using the United Kingdom Infrared Telescope's (UKIRT) spectrometer, CGS4, and polarimeter, IRPOL2, we have obtained spectropolarimetry from 3.2 to 3.8 $\mu$m of the lines of sight toward GCS 3-II and GCS 3-IV. The observations were carried out on the night of 2003 August 11 (UT). IRPOL2 combines a Wollaston prism and rotating half-wave plate. Each Stokes $Q$ and $U$ spectrum resulted from object and sky exposures at each of four position angles of the half-wave plate.

Two major issues with these data should be borne in mind. Firstly, the CGS4 spectropolarimetry arrangement is not optimal; the dispersion due to the Wollaston prism precedes the slit, and so at least two precise alignments are necessary to avoid considerable instrumental polarization: (1) alignment between the slit-position angle and the Wollaston dispersion direction, and (2) alignment between the telescope nod and the slit-position angle. The latter is straightforward and catered for very precisely by the telescope and instrument control system. The former requires on-sky measurements in stable conditions, to ensure that the slit-position angle calibration is adjusted appropriately. In the case of these observations, conditions were not stable, and the target was at a large negative declination, so the alignment was known to be less than perfect. In the resulting data, there is indeed detectable excess instrumental polarization, compared to that normally expected. There is no evidence that it contains spectral features, consistent with its origin in throughput losses as a function of dispersed beam position on the slit. The second issue is the presence of ripples in the polarization spectrum, in this case having at least two "frequencies." Removal of this ripple was achieved as described by Adamson et al. (1999), and this appears to have been successful.

Because the polarization in any wavelength bin is a vector quantity, all binning processes were carried out on the $Q$ and $U$ spectra, and the binned results combined in the usual way to reproduce a binned polarization spectrum. The final binned polarization spectra are shown in Figure 1. The gaps in the observed spectra at 3.29–3.34 and 3.37–3.41 $\mu$m occur where data have been removed because of severe absorption in the hydrocarbon-containing optical cement in the IRPOL2 Wollaston prism.

## 3. THE LINE OF SIGHT TOWARD THE QUINTUPLET MEMBERS GCS 3-II, IV

The Quintuplet cluster lies about $14'$ northeast of the Galactic center (Nagata et al. 1990; Okuda et al. 1990). The visual extinction along the line of sight is estimated to be $\sim$29 mag (Figer et al. 1999). The line of sight toward the Quintuplet sources includes both diffuse ISM and dense-cloud material (Schutte et al. 1998; Okuda et al. 1990; Chiar et al. 2000). However, the majority of the absorption arises in the diffuse ISM, as evidenced by the observation of weak 3.0 $\mu$m $H_2O$-ice features toward GCS 3-I and GCS 3-IV (Chiar et al. 2000).[8] Assuming a Taurus-like correlation between $A_V$ and $\tau_{3.0}$ (see Whittet et al. 2001), we estimate that approximately 6 mag of $A_V$ can be attributed to dense clouds.

Near-infrared observations of continuum polarization toward the Quintuplet sources show vectors that lie along the Galactic plane, indicating that it is interstellar in origin and induced by magnetically aligned dust grains (Kobayashi et al. 1983; Okuda et al. 1990). Silicate feature absorption and corresponding polarization at 9.7 $\mu$m is reported toward GCS 3-II and GCS 3-IV by Smith et al. (2000). The $p(\lambda)$ profiles are consistent with pure absorptive polarization (Smith et al. 2000). The position angle of the silicate polarization observed toward GCS 3-II and GCS 3-IV is essentially constant across the feature and similar to the interstellar value, and there is no underlying emission component to complicate the analysis. Therefore, it is unlikely that the silicate feature has a circumstellar component; it is safe to assume that it is carried by general ISM dust along the line of sight. The 9.7 $\mu$m features have peak optical depths $\tau = 2.9$ and 3.2 in GCS 3-II and GCS 3-IV, respectively. The corresponding peak polarizations ($p$) are 9% $\pm$ 0.3% and 10.2% $\pm$ 1.5%. Based on the observed polarization spectra, Smith et al. (2000) deduce the polarization excess ($\Delta p$) above the continuum to be 8% and 8.2% for GCS 3-II and GCS 3-IV, respectively. A measure of the polarization efficiency of the feature is then given by the ratio $\Delta p/\tau$, which is comparable (2.8 for GCS 3-II and 2.6 for GCS 3-IV) between the two sources.

[8] Based on observations with the *Infrared Space Observatory*'s (*ISO*) Short Wavelength Spectrometer (SWS). The $14'' \times 20''$ *ISO*-SWS beam was centered on GCS 3-I, and included all four GCS 3 objects.

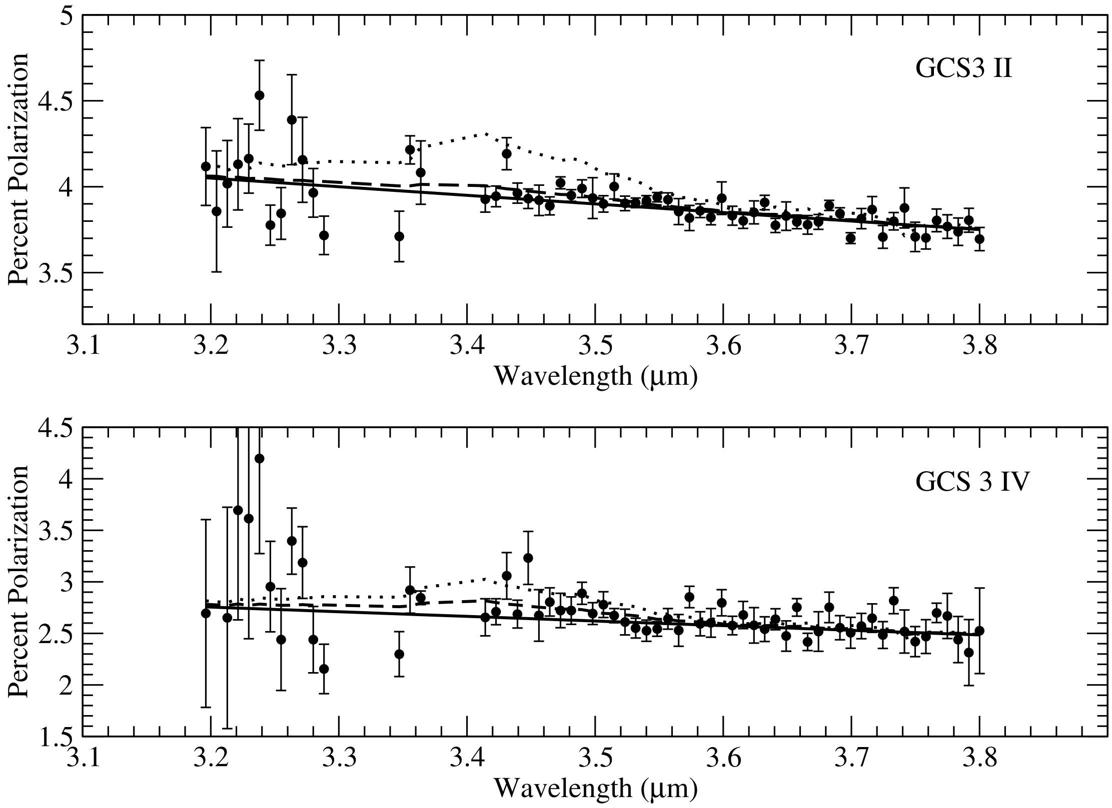


Fig. 1.— Polarization spectra of GCS 3-II (*top*) and GCS 3-IV (*bottom*). Observed polarization is shown by the filled circles with error bars. The estimated continuum polarization is shown by the solid line. The maximum allowed polarization, as determined from a $\chi^2$ fit in the 3.4 $\mu$m feature, is shown by the dashed line. The maximum polarization predicted for grains with organic mantles, assuming that $\Delta p/\tau$ is the same as for the silicates, is shown by the dotted line.

The 3.4 $\mu$m hydrocarbon absorption feature has been observed toward several Quintuplet cluster sources. Chiar et al. (2000) deduce $\tau_{3.4} = 0.16$ for GCS 3-I, based on spectroscopy with the Short Wavelength Spectrometer of the *Infrared Space Observatory.* J. E. Chiar et al. (2006, in preparation), using higher spatial resolution UKIRT-CSG4 data, find that the depth of the 3.4 $\mu$m feature is spatially invariant. They measure the optical depth to be $\tau_{3.4} = 0.17$ toward five lines of sight toward the Quintuplet (including GCS 3-II and GCS 3-IV). Thus, like the silicates, the hydrocarbons reside in the diffuse ISM along the line of sight and are unlikely to be local to the sources themselves.

## 4. SPECTROPOLARIMETRY OF THE 3.4 $\mu$m HYDROCARBON FEATURE

Based on the observed optical depth and polarization of the silicate feature, it is straightforward to predict that if the 3.4 $\mu$m feature is the result of ORM attached to silicate cores, it should be similarly polarized with $\Delta p \approx 0.47\%$ (GCS 3-II) and 0.44% (GCS 3-IV). Figure 1 shows that the filtered, reconstituted polarization spectra (*filled circles with error bars*) of both GCS 3-II and GCS 3-IV are to be essentially featureless. To estimate the maximum allowable polarization signal in the 3.4 $\mu$m feature, a plausible continuum polarization was traced that fits the observed $p(\lambda)$ spectrum at 3.2 and 3.7–3.8 $\mu$m (*solid line*). We created a model polarization spectrum using the average hydrocarbon spectrum calculated by Chiar et al. (2002; their Fig. 6) and assuming $\Delta p/\tau$ for the hydrocarbon feature to be equal to that of the silicate feature. We then carried out a least-squares fit, in order to minimize the residuals between the binned polarization data and model spectrum. The free parameter was $\Delta p$, the polarization above continuum at the peak of the modeled band. The maximum allowable polarization above the continuum is shown by the dashed line in Figure 1. The best fits are $0.06\% \pm 0.13\%$ for GCS3-II and $0.15\% \pm 0.31\%$ for GCS3-IV, consistent with zero in both cases, and well below the predicted level (shown by the dotted line in Fig. 1). The uncertainties quoted are formal 99% confidence limits, but ignore possible systematic errors in continuum placement. The largest uncertainty is probably in the continuum placement at the short-wavelength end of the spectrum; but plausible placements of the continuum level result in differences no greater than 0.02% in the fitted feature strength and do not therefore substantially alter the conclusions.

## 5. IMPLICATIONS FOR THE NATURE OF THE HYDROCARBON DUST

We have extended the search for polarization associated with the 3.4 $\mu$m absorption feature (Adamson et al. 1999) to two additional lines of sight, with consistent results: the feature is essentially unpolarized. The Adamson et al. study made a plausible comparison between their observed limit toward GC IRS7 and the predicted polarization excess for absorbers located on aligned silicate grains, but the conclusions were subject to an assumed lack of spatial variation in the silicate feature, as described in § 1. This ambiguity has now been removed. Based on models of the polarization properties of silicate and carbonaceous analog material, it has been suggested (Li & Greenberg 2002) that polarization across the 3.4 $\mu$m feature could be weaker per unit optical depth, compared to the silicate feature. Li & Greenberg (2002) consider mantle/core volume ratios (mantle thicknesses) of $V_{\rm carb}/V_{\rm sil} = 0.25$, 1, and 2, for spheroids over a range of elongations. For the most extreme case of a thick mantle ($V_{carb}/V_{sil} = 2$), the polarization of the 3.4 $\mu$m feature could be up to 25% weaker per unit optical depth, compared to the silicate feature, without violating the ORM model. Our data show that the observed polarization across the 3.4 $\mu$m feature is well below even this prediction.

We conclude that the agent responsible for the hydrocarbon feature in the diffuse ISM is located in a grain population that is both physically separate from the silicates and far less efficient as a producer of polarization. A good candidate is a population of very small carbonaceous grains that are optically isotropic and/or unresponsive to the alignment mechanism. A likely source of such grains is indicated by the observations of Chiar et al. (1998), who find a 3.4 $\mu$m feature essentially identical to the interstellar feature in the outflow of a C-rich evolved star. In contrast, molecular clouds exposed to significant UV flux, presumed to be the formation sites of ORM, show a conspicuous absence of the 3.4 $\mu$m feature (Shenoy et al. 2003). Amorphous carbon grains entering the ISM from the winds of evolved stars will readily become hydrogenated. An excellent spectroscopic match is obtained to the observed deformation modes, as well as to the C–H stretch, with laboratory analogs produced by hydrogenation of nano-sized carbon grains (Chiar et al. 2000; Mennella et al. 2002). Hydrogenated carbon grains are also good candidates for the 217.5 nm extinction bump, a ubiquitous feature of the extinction curve in the diffuse ISM (Schnaiter et al. 1999), which is also observed to be devoid of polarization in all but two (out of 30) lines of sight studied (Clayton et al. 1992, 1995; Somerville et al. 1994; Wolff et al. 1997).

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