THE ASTROPHYSICAL JOURNAL, 465:L61–L64, 1996 July 1

INTERSTELLAR POLARIZATION FROM CO AND XCN MANTLED GRAINS: A SEVERE TEST FOR GRAIN ALIGNMENT MECHANISMS

A. CHRYSOSTOMOU,[1] J. H. HOUGH,[1] D. C. B. WHITTET,[2] D. K. AITKEN,[1] P. F. ROCHE,[3] AND A. LAZARIAN[4]

Received 1996 February 14; accepted 1996 April 22

ABSTRACT

We present linear spectropolarimetry in the wavelength range 4.5–4.8 μm of the embedded infrared source W33A. Our observations show for the first time the presence of polarization associated with the CO and XCN ice features, demonstrating that the absorbers reside in or on aligned grains. Both narrow and broad components of the solid CO feature near 4.67 μm are polarized. The detection of polarization associated with the narrow CO component is particularly significant, as the ices responsible are thought to exist only in dense, cold regions of molecular clouds, where gas and grain temperatures are expected to be closely coupled and traditional grain alignment mechanisms should become ineffective. We discuss the significance of this result with regard to current grain alignment theories. Mechanisms in which grain rotational energy is enhanced by interaction with cosmic rays merit further investigation.

Subject headings: dust, extinction — ISM: individual (W33A) — ISM: magnetic fields — polarization

1. INTRODUCTION

Excess polarization corresponding to solid state absorption features arising in interstellar dust is expected if the absorbers are located in the component of the dust responsible for the general polarization of starlight. Spectroscopic and spectropolarimetric observations of these features provide a powerful diagnostic tool for investigating the optical properties of the grains and mechanisms for their alignment (Aitken 1989). To date, observers have succeeded in detecting linear polarization associated with the 3.1 μm feature of water ice and the 9.7 and 18.5 μm features of silicates (Dyck & Londsale 1981; Hough et al. 1988, 1989, 1996; Aitken, Smith & Roche 1989). The presence of polarization attributed to both ice and silicate material in the same lines of sight strongly suggests that core-mantle grains are aligned within molecular clouds. Magnetic alignment mechanisms, based on the classical Davis & Greenstein (1951, hereafter DG) theory and its modern formulations (see Roberge 1996) depend on the maintenance of a temperature difference between the dust grains and the gas in which they are immersed. The efficiency of alignment should therefore decline with increasing density in cold molecular cloud cores as the gas and dust temperatures become collisionally coupled. A rigorous observational test is to seek polarization excesses associated with ices more volatile than H_2O. The best candidate is CO, expected to condense and survive on the surfaces of grains at temperatures $T < 17$ K in clouds with gas densities $n > 10^4$ cm^{-3} (Léger 1983). In this Letter, we report the first detection of linear polarization in the solid CO absorption feature in the line of sight to W33A.

W33A is a compact infrared source with a particularly rich solid state molecular spectrum. It is generally assumed to be a young stellar object (YSO) but its precise evolutionary status is unclear (Mitchell et al. 1990). Its infrared spectrum is dominated by extremely deep solid state absorption features of water ice and silicates ($\tau_{3.1} > 5.4$ and $\tau_{9.7} \approx 7.8$, respectively; Willner et al. 1982). Other features detected in W33A are associated with CO, CH_3OH, hydrocarbons, and N-bearing molecules (Willner et al. 1982; Lacy et al. 1984; Grim et al. 1991; Tielens et al. 1991; Allamandola et al. 1992). The 4.5–4.8 μm spectral region investigated here contains the 4.67 μm resonance of solid CO and a broad feature centered at 4.62 μm, the latter attributed to the $C \equiv N$ bond in an as yet unidentified species (XCN) such as an isonitrile (Tegler et al. 1995). The solid CO feature itself is composite, consisting of superposed narrow and broad components, thought to represent CO in nonpolar (H_2O-poor) and polar (H_2O-rich) ice matrices, respectively (Tielens et al. 1991). The relative strengths of the CO and XCN features vary from source to source. CO is quite commonly observed in both YSOs and background stars toward molecular clouds (e.g., Chiar et al. 1995) whereas the XCN has been detected to date only in a relatively small number of YSOs (and is strongest in W33A; Tegler et al. 1995). These results provide compelling evidence for the evolution of ices as a function of environment: whereas nonpolar solid CO represents a pristine ice condensate formed in a cold, shielded environment, XCN is formed by energetic processing of nitrogenous ices in regions exposed to radiation from the embedded YSO (Lacy et al. 1984).

Mitchell et al. (1988, 1990) used high-resolution spectroscopy of the fundamental vibration-rotation band to show that gas phase CO in the line of sight to W33A is located in two distinct regions with different temperatures: a warm component at ~120 K and a much colder one at ~23 K. The warm gas is inferred to be near the embedded source and heated by its radiation, while the cool gas is very likely in the cold core of the W33 molecular cloud. It is highly probable that nonpolar CO ice exists only in the cold region. However, laboratory experiments show that CO may be retained at significantly higher temperatures as an impurity trapped in a matrix dominated by other, less volatile molecular ices (Lacy et al. 1984; Schmitt, Greenberg, & Grim 1989). For example, Schmitt et al. found that an H_2O-CO mixture containing 25%

---

[1] Division of Physical Sciences, University of Hertfordshire, College Lane, Hatfield, Hertfordshire, AL10 9AB, UK.

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

[3] Department of Astrophysics, University of Oxford, Keeble Road, Oxford, OX1 3RH, UK.

[4] Department of Astrophysical Sciences, Princeton University, Peyton Hall, Princeton, NJ 08544.

1996ApJ...465L..61C

CO at 10 K retains ~8% CO when warmed to 100 K. Some CO might therefore be present in polar ices in the warm cloud component toward W33A.

2. OBSERVATIONS

W33A (R.A. $18^{\rm h}11^{\rm m}44\overset{\rm s}{.}6$, Decl. $-17°52'57''$, 1950) was observed on the night of 1995 September 15 with the 3.8 m United Kingdom Infrared Telescope (UKIRT), Mauna Kea, Hawaii. The instrument used was the recently upgraded cooled grating spectrometer CGS4, now equipped with a 256×256 InSb array. The spectropolarimetry mode of CGS4 has also recently been upgraded with a new module, designed and built at the University of Hertfordshire, which includes a cold Wollaston prism as the polarization analyzer. The data for W33A presented here were obtained in 13 minutes on-source integration at a spectral resolution of 0.0025 μm. Flux calibration and atmospheric cancellation were performed by observing BS 7120, a K3 II standard star with apparent magnitude 2.11 in the *M* passband. Flat-fielding with CGS4 is normally achieved by exposing the detector array to an internal blackbody lamp, but due to the smaller well depth of the new array it was not possible to do this without saturating the detectors. A first-order flat-field was performed during sky subtraction, and we note that, in principle, polarimetry is independent of the flat-field. Errors in our data are calculated from repeated observations of the source. Features in our spectrum and discrete atmospheric features provided wavelength calibration.

The incoming radiation is split within CGS4 into the orthogonally polarized extraordinary (e) and ordinary (o) rays. Upstream of CGS4, a half-wave retarder in the polarimetry module is rotated to four angular positions (0°, 45°, $22\overset{\circ}{.}5$, and $67\overset{\circ}{.}5$) and the intensities $I_{\rm e}$ and $I_{\rm o}$ of the e and o rays are measured at each of these positions. Stokes parameters are then calculated: from the 0° and 45° data, $Q = (R_Q - 1)/(R_Q + 1)$, where $R_Q^2 = (I_{\rm e}/I_{\rm o})_0/(I_{\rm e}/I_{\rm o})_{45}$, and similarly the $22\overset{\circ}{.}5$ and $67\overset{\circ}{.}5$ data yields U. Individual Q and U spectra were co-added. The degree p and position angle θ of polarization at each point in the spectrum were then calculated from the final Q and U spectra in the usual way, i.e., $p^2 = (Q^2 + U^2)/I^2$ and $\theta = 0.5$ arctan (U/Q). Calibration of θ was obtained with reference to observations of GL 2591 (Hough et al. 1989).

A ripple or beating pattern of amplitude ~2% and period ~0.015 μm is apparent in the normalized Q and U spectra. Although small, its amplitude is larger than the point-to-point errors. This phenomenon has previously been seen in optical spectropolarimetry (Adamson & Whittet 1995). We believe it is caused by interference between reflections from the waveplate components, which affects the Q and U determinations because of slight nonparallelism. To remove it, a Fourier analysis of the Q/I and U/I spectra was carried out, and the periods at which the ripple occurs were identified from the power spectrum. These periods were eliminated from the Fourier transform and the spectra were then reconstituted. The results obtained were highly satisfactory, with the ripple pattern eliminated and just the real noise of the spectra remaining.

3. RESULTS AND DISCUSSION

Figure 1 shows the results of our spectropolarimetry. All data are binned into 3-pixel elements. The lower, middle, and upper frames of Figure 1 show the flux density, position angle, and degree of linear polarization, respectively. The absorption features of XCN (~4.62 μm) and CO (~4.67 μm), first reported by Lacy et al. (1984), are prominent in our flux spectrum. The continuum polarization of W33A is exceptionally high in the near-infrared: our data indicate $p = 9.0 \pm 0.1\%$ at 4.8 μm, consistent with previous measurements ($p = 15.6 \pm 1.0\%$ at 3.5 μm and $11.1 \pm 0.4\%$ at 4.0 μm from Hough et al. 1989; $p = 5.3 \pm 0.6\%$ at 8.0 μm from Wright 1994). The polarization position angle is constant to within measurement errors, both within our data set and in comparison to data in the 3 and 10 μm windows.

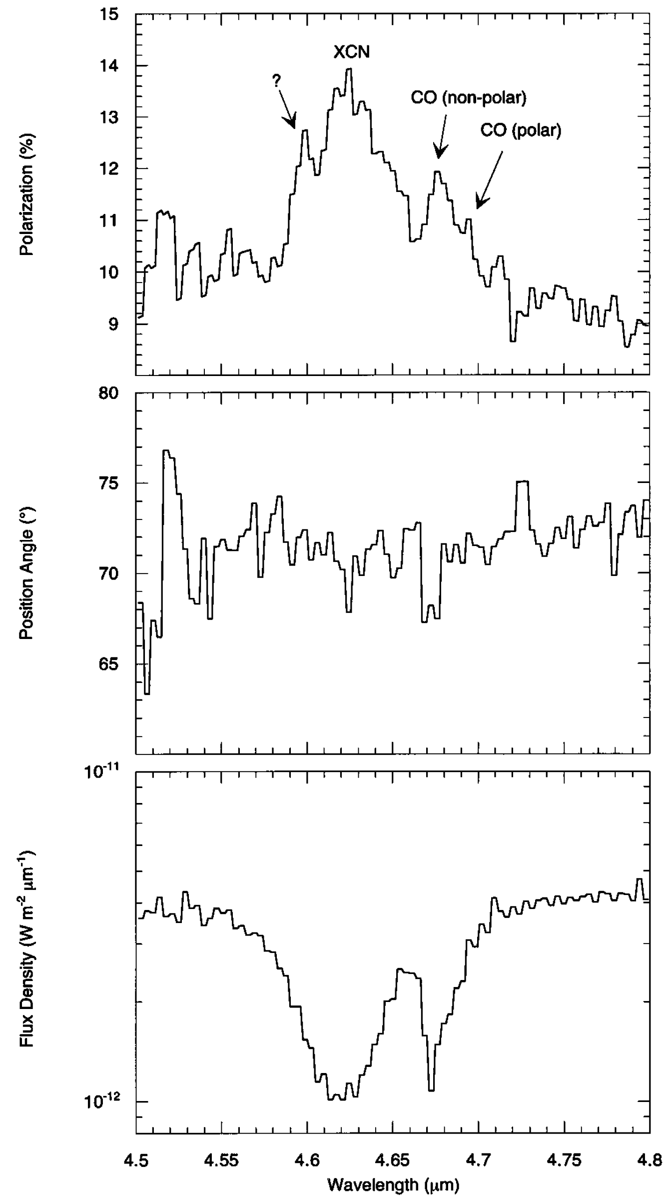

FIG. 1.—Plots of degree of polarization (*upper frame*), position angle of polarization (*middle frame*), and flux density (*lower frame*) vs. wavelength in the spectral range 4.5–4.8 μm from our observations of W33A. See text for further details.

Comparing upper and lower frames in Figure 1, there is clear evidence for peaks in the degree of polarization which correspond to the absorptions of XCN and CO. This is the first

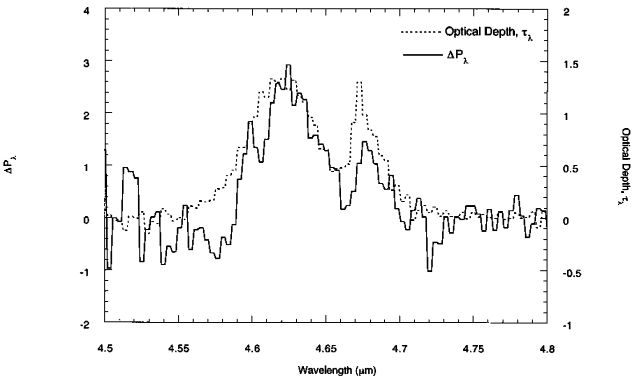

FIG. 2.—Plots of excess polarization Δp (*solid curve*, *left-hand scale*) and optical depth τ (*dashed curve*, *right-hand scale*) vs. wavelength, as deduced from our observations.

time that excess polarizations have been detected in these features for any object. In the case of CO, the polarization data show the same asymmetry seen in absorption, suggesting that the narrow and broad components (see § 1) are both present in polarization. Some substructure might also be present in the XCN feature near 4.60 μm, the origin of which is unclear.

Optical depths $\tau(\lambda)$ and excess polarization $\Delta p(\lambda)$ in the XCN and CO features were calculated by fitting to adjacent continuum in both flux and polarization spectra. Results are superposed in Figure 2. Peak optical depths in both XCN and CO features are ~1.3, consistent with previous estimates (see Tegler et al. 1995). The excess polarization in the XCN feature is 3.0 ± 0.2%, and that in the CO ice feature is 1.4 ± 0.2%. Note that the peaks in $p(\lambda)$ for the XCN and CO features are shifted to slightly longer wavelength relative to the corresponding peaks in $\tau(\lambda)$, as expected if the polarization is produced by dichroism rather than scattering: the absorption coefficients of nonspherical grains are different for radiation polarized perpendicular and parallel to the axis of symmetry, shifting the polarization peak to longer wavelengths relative to the extinction at a resonance (see Kobayashi et al. 1980; Aitken 1989). This result confirms that the observed polarization excesses are produced by dichroic absorption of aligned grains. We regard this as definitive proof that XCN and CO ice mantled grains are aligned along the line of sight to W33A.

The ratio $\Delta p(\lambda)/\tau(\lambda)$ is a factor ~2 higher for the XCN feature compared with the CO feature (2.3% compared with 1.0%). This might imply that grains containing XCN are better aligned that those containing CO, although both appear to have $\Delta p(\lambda)/\tau(\lambda)$-values of the same order as observed in the H_2O ice and silicate features toward other YSOs (Aitken 1996). It seems that grains are able to align to some degree in a wide range of situations, regardless of the presence of a mantle or its composition. This tends to suggest that it is the nature of the grain *core* which is crucial for grain alignment.

A preliminary attempt has been made to model the profile of the CO feature in our flux spectrum of W33A with laboratory data, the results of which will be reported in detail elsewhere (Chiar et al. 1996). The CO feature was extracted from the blended spectrum by fitting a Gaussian to the XCN profile. Fits to the CO profile were attempted with all available combinations of mixtures for the polar and nonpolar components (see Chiar et al. 1995 for a description of techniques and laboratory data). The best fit was obtained using a 10:1 CO:H_2O mixture at 10 K for the nonpolar component and a 4:1 H_2O:CO mixture at 100 K for the polar component. An almost equally good fit was obtained with pure CO at 10 K for the nonpolar component and an irradiated 2:1 H_2O:CH_3OH mixture at 10 K for the polar component. The narrow component cannot be fit with a mixture in which H_2O is more abundant than CO, consistent with results for other lines of sight: the mantles containing the nonpolar component of the ices must therefore have $T < 20$ K. The polar component may arise in either thermally or radiatively processed ices.

4. IMPLICATIONS FOR GRAIN ALIGNMENT

Any anisotropic component in the distribution of grain spins will result in alignment by the ambient magnetic field, irrespective of the mechanism producing the anisotropy (Aitken 1992; Dolginov & Mytraphonov 1976). This is because a magnetic moment is induced in the spinning grains (Barnett effect) and this moment precesses around the magnetic field with a period less than the timescale of any disruptive processes. However, the mechanism which produces the initial anisotropy is not well understood, and there might be a large number of such processes, each important in different situations. The classical DG alignment mechanism relies on internal energy dissipation within the grain (paramagnetic relaxation) leading to rotation about the axis of greatest moment of inertia, which in turn becomes aligned by the ambient magnetic field. However, other factors contrive to inhibit the DG alignment mechanism. In particular, it will only operate if a difference is maintained between the gas temperature and the internal temperature of the grain (Jones & Spitzer 1967). In general, the magnetic field strengths required to align the grains in competition with randomizing gas collisions are ~10 times greater than those typically observed in the ISM. Moreover, the DG mechanism predicts better alignment of smaller grains, contrary to observations of interstellar polarization (Whittet 1996).

Several processes have been proposed to enhance the alignment mechanism. Purcell (1979) suggested a pinwheel effect in which H_2 forms preferentially at certain sites on a grain surface. Subsequent ejection of H_2 results in a nonrandom torque, which serves to provide efficient suprathermal grain spin (see Lazarian 1995 for recent discussion). However, it is not clear how the location of ejection sites could remain constant while the grain is accreting a mantle. Another enhancement process, first proposed by Jones & Spitzer (1967), assumes that the imaginary part of the susceptibility (which leads to internal dissipation) is greatly enhanced by clusters of ferromagnetic atoms or molecules. This can naturally explain why larger grains are better aligned than smaller grains, since there is a higher probability for the larger grains to contain ferromagnetic inclusions (Mathis 1986). Moreover, much weaker magnetic fields can lead to alignment. Provided that the number of inclusions is not too high, the grain remain superparamagnetic (rather than ferromagnetic) and the basic principles of the DG mechanism still apply, which thus still requires a difference between the dust kinetic and rotational temperatures.

Our discovery of polarization in the CO ice feature is extremely important for constraining such theoretical models. As already noted, nonpolar CO mantles occur only in relatively dense, cold locations within molecular clouds, where the temperature difference between gas and grains is expected to approach zero. As virtually all hydrogen is already in molecular form in such regions, it is hard to appeal to the Purcell mechanism to increase the effective rotational temperature of the grains. In this situation, even grains with superparamagnetic inclusions cannot be aligned by DG-type processes.

The possible relevance of cosmic rays to grain alignment was first discussed by Purcell & Spitzer (1971). Although unlikely to play a significant role in diffuse regions, they might provide an important source of rotational energy for grains deep within molecular clouds. Sorrell (1995) suggested that a cosmic-ray–driven pinwheel mechanism might align mantled grains in molecular clouds: it is argued that ejection of H_2 from hot spots formed on a mantled grain after passage of a cosmic ray may lead to spin-up and hence provide an anisotropy to the grain spin distribution. However, the mechanism is sensitive to the composition of the ice mantle and predicts alignment of grains coated with H_2O but not with CO, inconsistent with our observations. Purcell & Spitzer (1971) showed that cosmic rays may deposit their angular momentum while passing through grains, resulting in spin-up with efficiency dependent on the spectrum of cosmic rays at the low energy cutoff. Lazarian & Roberge (1996) show that this process is not negligible for realistic cosmic-ray spectra.

Another mechanism which shows some promise is that of Gold (1952), in which alignment of grains drifting through the gas is driven by anisotropic angular impulses imparted by gas-grain collisions. Differential motion may arise from the effect of Alfvén waves (Lazarian 1994) or ambipolar diffusion (Roberge, Hanany, & Messinger 1995). A necessary requirement for alignment by Alfvén waves is the presence of supersonic gas. Goldsmith & Mao (1983) showed that ^{13}CO emission lines in the direction of W33A have widths ~ 8 km s^{-1} (see also Mitchell et al. 1988), and for an adiabatic molecular gas this velocity may be considered to be supersonic. However, it is unlikely that these motions occur in the same locations as the nonpolar CO mantles; the line widths are probably dominated by warmer gas closer to the source. The original Gold process of alignment through grain acceleration by radiation pressure also seems improbable, because of the instability of volatile CO mantles to irradiation; but if the incident radiation is dominated by soft infrared photons, this mechanism might still be feasible.

Our results may be contrasted to those of other recent studies (Goodman et al. 1995; Gerakines, Whittet, & Lazarian 1995), which provide independent evidence for a rapid decline in the efficiency of continuum interstellar polarization of background starlight with density in dark clouds. The implication is that alignment becomes much less efficient deep within the clouds, consistent with theoretical predictions. One possible explanation might be that, in lines of sight to embedded objects such as W33A, the source itself provides conditions leading to efficient alignment of the grains in its vicinity. An observational test of this possibility would be to search for polarization excess in the CO feature along the line of sight to a background field star that clearly does not influence the physical conditions within the foreground molecular cloud. A good candidate is Elias 16, which lies behind the Taurus dark cloud; it has already been shown that H_2O-ice absorption in this line of sight is produced by aligned grains (Hough et al. 1988).

The authors would like to thank the UK Panel for the Allocation of Telescope Time for continued support of this program. A. C. thanks the UK Particle Physics and Astronomy Research Council for a postdoctoral research associateship. D. C. B. W. and A. L. are funded by NASA grants NAGW 3144 and NAG5-2858, respectively. D. K. A. acknowledges with thanks the support of a Leverhulme Trust grant. We are grateful to the technical staff at the University of Hertfordshire for constructing the waveplate modules, and to the UKIRT staff for valuable help during commissioning. We also thank Andy Adamson for advice on removal of ripple patterns, and Jean Chiar for results of CO profile modeling in advance of publication.

REFERENCES

Adamson, A. J., & Whittet, D. C. B. 1995, ApJ, 448, L49
Aitken, D. K. 1989, in Infrared Spectroscopy in Astronomy, ed. B. H. Kaldeich (ESA Pub. SP-290), 99
———. 1992, Australian J. Phys., 45, 569
———. 1996, in Polarimetry of the Interstellar Medium, ed. W. G. Roberge & D. C. B. Whittet (San Francisco: ASP), in press
Aitken, D. K., Smith, C. H., & Roche, P. F. 1989, MNRAS, 236, 919
Allamandola, L. J., Sandford, S. A., Tielens, A. G. G. M., & Herbst, T. M. 1992, ApJ, 399, 134
Chiar, J. E., Adamson, A. J., Kerr, T. H., & Whittet, D. C. B. 1995, ApJ, 455, 234
Chiar, J. E., et al. 1996, in preparation
Davis, L., & Greenstein, J. L. 1951, ApJ, 114, 206
Dolginov, A. Z., & Mytraphonov, J. G. 1976, Ap&SS, 43, 291
Dyck, H. M., & Londsale, C. J. 1981, in IAU Symp. 96, Infrared Astronomy, ed. C. G. Wynne-Williams & D. P. Cruickshank (Dordrecht: Reidel), 223
Gerakines, P. A., Whittet, D. C. B., & Lazarian, A. 1995, ApJ, 455, L171
Gold, T. 1952, MNRAS, 112, 215
Goldsmith, P. F., & Mao, X.-J. 1983, ApJ, 265, 791
Goodman, A. A., Jones, T. J., Lada, E. A., & Myers, P. C. 1995, ApJ, 448, 748
Grim, R. J. A., Baas, F., Geballe, T. R., Greenberg, J. M., & Schutte, W. 1991, A&A, 243, 473
Hough, J. H., et al. 1988, MNRAS, 230, 107
———. 1989, MNRAS, 241, 71
Hough, J. H., Chrysostomou, A., Messinger, D. W., Whittet, D. C. B., Aitken, D. K., & Roche, P. F. 1996, ApJ, 461, 902
Jones, R. V., & Spitzer, L. 1967, ApJ, 147, 943
Kobayashi, Y., Kawara, K., Sato, S., & Okuda, H. 1980, PASJ, 32, 295
Lacy, J. H., et al. 1984, ApJ, 276, 533
Lazarian, A. 1994, MNRAS, 268, 713
———. 1995, MNRAS, 274, 679
Lazarian, A., & Roberge, W. G. 1996, in preparation
Léger, A. 1983, A&A, 123, 271
Mathis, J. S. 1986, ApJ, 308, 281
Mitchell, G. F., Allen, M., & Maillard, J.-P. 1988, ApJ, 333, L55
Mitchell, G. F., Maillard, J.-P., Allen, M., Beer, R., & Belcourt, K. 1990, ApJ, 363, 554
Purcell, E. M. 1979, ApJ, 231, 404
Purcell, E. M., & Spitzer, L. 1971, ApJ, 167, 31
Roberge, W. G. 1996, in Polarimetry of the Interstellar Medium, ed. W. G. Roberge & D. C. B. Whittet (San Francisco: ASP), in press
Roberge, W. G., Hanany, S., & Messinger, D. W. 1995, ApJ, 453, 238
Schmitt, B., Greenberg, J. M., & Grim, R. J. A. 1989, ApJ, 340, L33
Sorrell, W. H. 1995, MNRAS, 273, 169
Tegler, S. C., Weintraub, D. A., Rettig, T. W., Pendleton, Y. J., Whittet, D. C. B., & Kulesa, C. A. 1995, ApJ, 439, 279
Tielens, A. G. G. M., Tokunaga, A. T., Geballe, T. R., & Baas, F. 1991, ApJ, 381, 181
Whittet, D. C. B. 1996, in Polarimetry of the Interstellar Medium, ed. W. G. Roberge & D. C. B. Whittet (San Francisco: ASP), in press
Willner, S. P., et al. 1982, ApJ, 253, 174
Wright, C. M. 1994, Ph.D. thesis, Univ. New South Wales