Aust. J. Phys., 1992, **45**, 581–9

8–13 μm Spectropolarimetry of Star Formation Regions*

Christopher M. Wright

Department of Physics, University College,
Australian Defence Force Academy, Canberra, A.C.T. 2600, Australia.

Abstract

Amongst other things, mid-infrared spectropolarimetry provides information on the direction of the transverse component of a magnetic field. The polarisation is produced by dichroic emission and/or absorption by dust grains whose alignment is controlled by the ambient magnetic field. The observed position angle of the $\boldsymbol{E}$ vector allows the field direction to be determined. Here results are presented of 8–13 μm spectropolarimetric observations of a number of star formation regions. Comparisons are made between the field direction observed and the Galactic field established by optical polarimetry of nearby field stars, and with the orientation of bipolar outflows and/or disks which are associated with some of these objects.

1. Introduction

Previous studies comparing the directions of infrared polarisation of protostellar sources with interstellar polarisation of nearby field stars have been carried out in the K band (2·2 μm) (Dyck and Lonsdale 1979; Heckert and Zeilik 1981; Sato *et al.* 1985). At such a wavelength however, the polarisation mechanism is uncertain. The two competing models are dichroic absorption through a medium of magnetically aligned dust grains, and scattering off dust grains in a non-spherical circumstellar shell. Both processes are probably required to fully explain all polarisation phenomena associated with infrared objects, especially those objects embedded in star formation regions.

In their study, Dyck and Lonsdale (1979) found a strong correlation between the direction of infrared polarisation of protostellar objects and the direction of interstellar polarisation in the immediate vicinity of the sources. In most cases they found the difference in the two directions to be less than 30°. They interpreted this as implying that the Galactic magnetic field plays an important part in the evolution of these sources, and that this conclusion is independent of the mechanism of infrared polarisation [although Dyck and Lonsdale (1981) refer to grain alignment as the likely polarising mechanism]. Heckert and Zeilik (1981) also found such a correlation, but in addition found a group of sources whose infrared polarisation is inclined by more than 45° to the interstellar field. They interpreted their distribution of sources with $|\theta_{\rm IR} - \theta_{\rm star}| < 30°$ as those whose

* Paper presented at the Workshop on Star Formation in Different Environments, held at the University of Sydney, 9–11 October 1991.

0004-9506/92/040581$05.00

polarisation mechanism is dichroic absorption through a region of magnetically aligned grains, and that the sources with $|\theta_{\rm IR} - \theta_{\rm star}| > 45°$ are polarised by scattering from an anisotropic disk. Their work also supported the importance of the Galactic magnetic field in the star formation process.

High velocity molecular outflows are now known to be an important phase in the early evolution of stars. In many cases, the outflow appears to be bipolar, with peaks of blue- and red-shifted CO emission arising from separate regions of the sky, often on opposite sides of a visually obscured infrared object, thought to be the object onto which material is accreting. In some cases, a disk or torus of material has been observed around the source, extending in a direction perpendicular to the axis of the outflow (e.g. Torrelles *et al.* 1983; Takano *et al.* 1984). In a study of the K band polarisation of ten infrared sources in bipolar CO outflows, Sato *et al.* (1985) found that the position angle of the polarisation is predominantly perpendicular to the outflow, and parallel to the disk (four sources). This result hints at some relationship between the direction of a magnetic field and the directions of disks and outflows in star formation regions. However, there is some ambiguity over the scattering/dichroic mechanism of polarisation. Sato *et al.* interpreted their polarisation as due to scattering, and recent computations by Bastien and Menard (1988, 1990) of multiple scattering in a disk lead to the expectation that the polarisation produced will lie in the plane of the disk. In this case the polarisation is independent of the presence of any magnetic field.

One way of resolving the difficulty concerning the mechanism responsible for the polarisation is to make spectropolarimetric observations at wavelengths longer than 2·2 μm. At 10 μm, the contribution from scattering polarisation is expected to be negligible. In confirmation of this, the peak in polarisation across the 9·7 μm silicate absorption feature is shifted to a longer wavelength than the peak in extinction, as expected for a dichroic polarisation mechanism (Martin 1975; Aitken 1989).

In this paper, we report results of 10 μm spectropolarimetric observations of star formation regions. In Section 3 we compare the direction of our observed magnetic field with the ambient interstellar field derived from optical polarimetry of nearby field stars. In Section 4 we examine the relationship between bipolar outflow and/or disk axes and the direction of the magnetic field deduced from our observations.

2. Observations and Source Selection

In this paper, I report the results of observations made by David Aitken and Craig Smith, also from ADFA, Patrick Roche from Oxford, and myself. The observations were made using the UCL 10 μm spectropolarimeter at the Cassegrain focus of three telescopes: the 3·9 m AAT, the 3·8 m UKIRT and the 3 m IRTF. Beam sizes employed were in the range of 4 to 6 arcsec. The effective resolving power of the instrument at 10 μm is about 40. Further details of the observing procedure can be found in Aitken *et al.* (1988).

Our sample of observed sources contains 22 objects. Many of them are included in the studies by Dyck and Lonsdale (1979) and Heckert and Zeilik (1981), but seven are unique to this study. All are associated with molecular clouds or HII regions; i.e. regions of ongoing star formation. A selection bias is contained within our sample, in that all of our objects are highly luminous and are examples of high mass star formation. This is simply an observational constraint on doing spectropolarimetry at 10 μm. Bright objects are required for adequate signal to noise.

For molecular clouds where we have made measurements at more than one position, we have used only the brightest position in the analysis. This eliminates the possibility of any one region being weighted too heavily. In contrast, Dyck and Lonsdale (1979) included such multiple measurements in their analysis.

All objects in the sample show evidence for silicate absorption in their spectra, with optical depths at 9·7 μm ranging from about 1 to about 7. Most are in fact deeply embedded infrared objects, this being especially true for those objects associated with bipolar outflows.

It is possible to observe two components in the polarisation spectrum using 10 μm spectropolarimetry; polarised emission and absorption (see the contribution by Aitken 1992, present issue p. 569). These components can be readily identified by their unique spectral forms, and are easily unfolded if present in the one source. Most objects in our sample show only the absorption component. For consistency, in those objects that display the two components, we only consider that due to absorption in the analysis, and we take the position angle to indicate the direction of the projected magnetic field.

3. Relationship between 10 μm Polarisation of Star Formation Regions and Nearby Interstellar Polarisation

The interstellar optical polarisation data were taken from the compilation of Axon and Ellis (1976). In order to critically compare the direction of the interstellar magnetic field with our observed field, we have used three criteria in selecting field stars, following from the work of Dyck and Lonsdale (1979). The selection criteria are (i) that the field stars bracket the distance to the infrared source, (ii) that the optical polarisation is greater than about 1% and (iii) that they are within a few degrees of the infrared object. These criteria aid in selecting stars whose polarisation is not affected by foreground or surrounding molecular clouds. However, even with these restrictions in place, many regions displayed a large scatter in the position angles of interstellar polarisation, so that the interstellar field could not be determined reliably. In other regions, few stars were found to satisfy all criteria, and one or more had to be relaxed in order to obtain sufficient statistics. In still other regions, due to the large distance to the source, no optical polarisation measurements were available.

Fig. 1 shows histograms for two regions, illustrating the number of stars in each 20° interval of position angle. One can see that in some cases, as in the vicinity of G333·6–0·2, the interstellar field is quite well determined, with only a small spread in position angles. However, in other cases, such as the region around RCW 57, the field is not as well determined, with a much larger spread in field star position angles.

Fig. 2 compares the direction of the 10 μm position angle with the interstellar field. It must be kept in mind that, apart from real differences in the polarisation directions, the width of the distribution in Fig. 2 is influenced by the dispersion in position angle inherent in many of the interstellar fields.

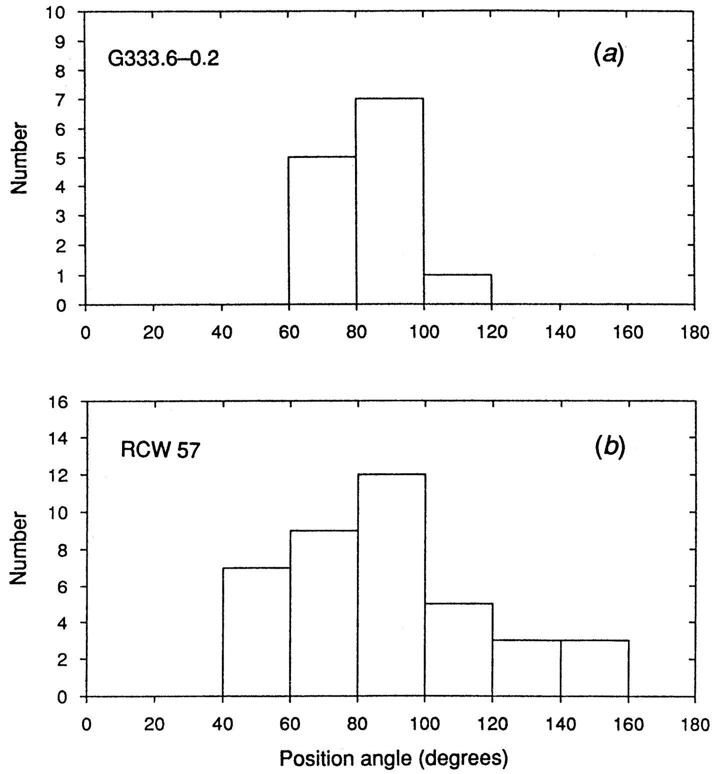

Fig. 1. Histograms of the distribution of optical interstellar polarisation position angle for field stars in the vicinity of the HII regions: (*a*) G333·6–0·2 and (*b*) RCW 57. The galactic coordinate system is used, and the position angle is measured positive from North through East.

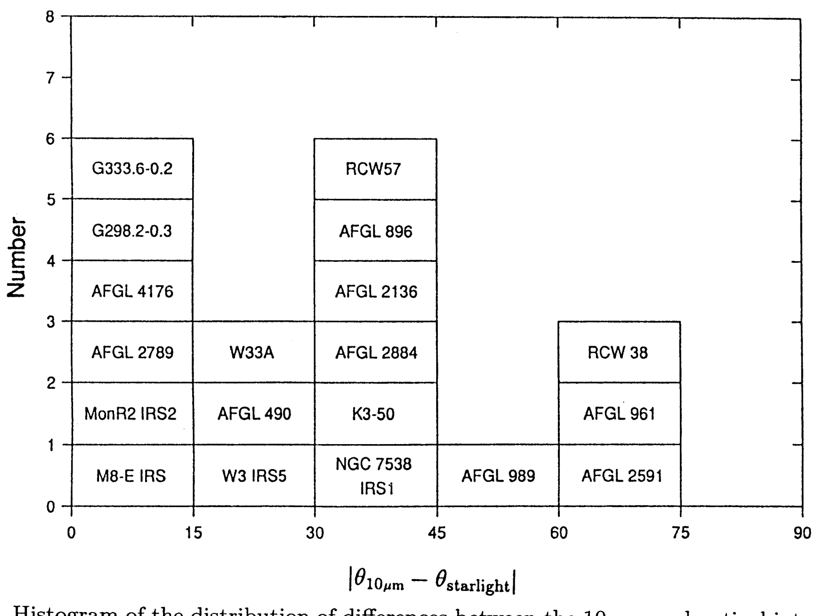

Fig. 2. Histogram of the distribution of differences between the 10 μm and optical interstellar polarisation position angles.

The histogram shows that the majority of infrared sources have magnetic fields inclined by less than 45° to the interstellar field (15 out of a total of 19 for which an interstellar field could be found). This can be compared with the results of Dyck and Lonsdale (1979) and Heckert and Zeilik (1981). Both these papers reported a strong tendency for the K band polarisation to be close to the interstellar field (i.e. within 30°), and concluded that the Galactic magnetic field has had a strong influence on the evolution of their sample of objects. Though the tendency for the two directions to be parallel is not as obvious in our more limited data set, our results are statistically consistent, and appear to support this conclusion.

4. Relationship between 10 μm Polarisation and Bipolar Outflows and Circumstellar Disks around Young Stellar Objects

We now examine geometrical relationships between the position angle of 10 μm polarisation, and the directions of bipolar molecular outflows and/or molecular disks/tori. Within our sample of observed sources, 13 are known to be sites of high velocity molecular outflow, 10 of which possess an unambiguous bipolar morphology, and for 9 of which a disk/torus has been observed by one or more means.

Evidence has steadily been accumulating over the last 10 years that stars in the very early stages of evolution undergo a phase of energetic mass ejection (see for example the review of Lada 1985). Such evidence is in the form of optical jets, fast moving Herbig–Haro objects and high radial velocity water masers. In addition, millimetre observations of rotational transitions in the CO molecule reveal high velocity, collimated mass outflow on scales larger than a parsec. In many cases, the outflow takes on a bipolar morphology (Fukui 1989), with peaks of red- and blue-shifted emission arising on either side of (in many cases) an embedded infrared object. Such bipolarity is inferred from contour maps of the integrated intensity in the red- and blue-shifted 'wings' of the CO emission line (e.g. Bally and Lada 1983; Snell *et al.* 1984).

Observations of several outflow sources have also recently indicated the presence of a flattened distribution of gas or dust, often referred to as a disk or torus, surrounding these objects and oriented perpendicularly to the bipolar outflow. The presence of such a structure is revealed from a number of different types of observations, some of which are:

(i) Maps of transitions in the CS and NH_3 molecules (e.g. Takano *et al.* 1984; Kawabe *et al.* 1984; Torrelles *et al.* 1983). The observed transitions in these molecules require high densities for their excitation, and so are ideal for probing such regions in areas of star formation. In some cases, a velocity gradient is found along the major axis of the flattened distribution of gas, implying rotation and providing further evidence for a disk.

(ii) Imaging polarimetry maps (e.g. Bastien and Menard 1988, 1990; Minchin *et al.* 1991*c*). Polarisation maps of bipolar outflow objects, made at optical and near infrared wavelengths, typically show a centrosymmetric pattern, characteristic of single scattering by dust grains in the lobes of the outflow. Polarisations up to 50% are frequently observed. Closer to the source of illumination however, the polarisation is reduced, and the vectors are aligned along a given direction. Initially this behaviour was ascribed to dichroic extinction by aligned grains

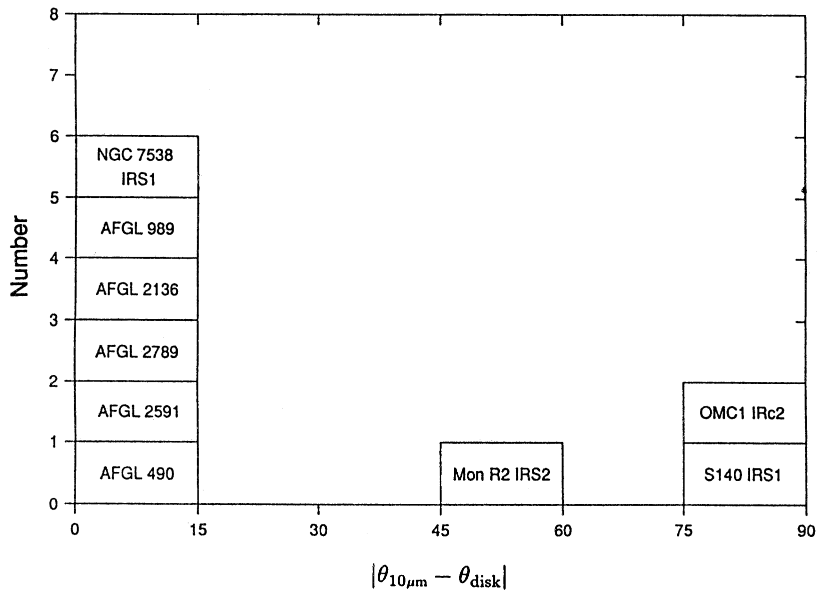

Fig. 3. Histogram of the distribution of differences between the 10 μm polarisation position angle and the position angle of the major axis of circumstellar disks/tori. This indicates that there is a magnetic field component preferentially oriented parallel to the disk.

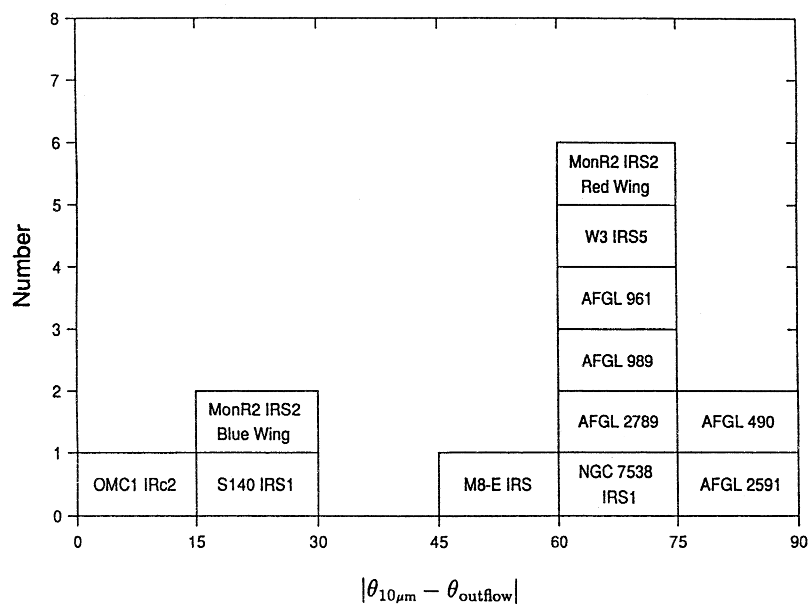

Fig. 4. Histogram of the distribution of differences between the 10 μm polarisation position angle and the position angle of the axis of bipolar molecular outflows. MonR2 IRS2 is included twice due to the peculiar bent morphology of its outflow (Wolf *et al.* 1990). The wings of red- and blue-shifted emission in this source are oriented along different position angles. The histogram indicates that there is a magnetic field component preferentially oriented orthogonal to the outflow.

in the plane of a disk, but recent arguments by Bastien and Menard (1988, 1990) have challenged this point of view. Instead, they believe that multiple scattering in an optically thick disk can account for the observed alignment. Their models reproduce the gross features of polarisation maps made at K and shorter wavelengths, and predict that the polarisation in the immediate vicinity of the object will lie in the plane of the disk. The question of which polarisation mechanism is operating close to the source is still an unresolved one, at least up to K, but it does seem that imaging polarimetry is able to delineate the plane of a circumstellar disk.

(iii) Maps of mm/sub-mm/far-infrared continuum dust emission (e.g. Sandell 1989; Walker *et al.* 1990). Sandell (1989) argued that maps made at such wavelengths are able to define the axes of disks surrounding outflow sources. This seems to be confirmed when comparisons are made with independent means as listed above.

Making use of observations of the type listed above, contained in the literature, we derived position angles of bipolar outflows (Lada 1985; Fukui 1989 and references therein; Mitchell *et al.* 1991) and disks (Walker *et al.* 1990; Minchin *et al.* 1991*b*, 1991*c*; Torrelles *et al.* 1983; Hayashi *et al.* 1987; Scoville *et al.* 1986; Plambeck *et al.* 1982) for several objects. We then compared the geometry of such structures with our 10 μm spectropolarimetric observations, a process which defines the direction of the magnetic field on the plane of the sky. The results of such a comparison are presented in Fig. 3. Immediately evident is that the direction of polarisation, and so the magnetic field, lies predominantly in the plane of the disk. Fig. 4 shows a similar comparison, this time for the axis of the outflow, from which it can be seen that the magnetic field is mostly orthogonal to the outflow. The reason for presenting the two figures is that for some objects we had both a disk and outflow direction, whilst for others we had just one or the other.

In a K band study, Sato *et al.* (1985) found a similar relationship to exist between infrared polarisation and outflow and disk/torus axes. At that time however, only four of their objects had been observed to possess a disk, three of which are not contained in our study, and the fourth of which (AFGL 490) is in agreement with our result. For the three objects unique to their study (L1551 IRS5, NGC 2071 and R Mon), Sato *et al.* found that the position angle at K was parallel to the disk, and orthogonal to the outflow. Hodapp (1984), again at K, found a similar result when he compared his position angles with the bipolar flow axes. Contained in his observed sample were sources not observed by us or Sato *et al.* (1985) (DG Tau, HH7–11, HL Tau and CepA IRS3), some of which are examples of low mass star formation. Both Sato *et al.* and Hodapp interpreted their data as due to a scattering polarisation mechanism. If instead the polarisation mechanism operating at K is the same as that at 10 μm, then their results add further to the evidence of a toroidal magnetic field existing in circumstellar disks.

The observed scenario of magnetic field and disk structures toward embedded infrared objects being parallel is not favoured by recent models proposed to explain the generation and collimation of bipolar molecular outflows (Pudritz and Norman 1983, 1986; Pudritz 1985). Such models predict a poloidal, rather than the observed toroidal, field. Exceptions to the observed norm, and which seem to fit in with the models, are Mon R2, S140 IRS1, and OMC1 IRc2. However, the case of IRc2 is an intriguing one. The 10 μm position angle observed for this source is close to the angle observed at BN (Aitken *et al.* 1985), and it is not clear at all whether we are probing the field in the disk around IRc2, or instead looking at part of a large-scale field threading the entire infrared cluster in the cloud. In fact Minchin *et al.* (1991*a*) presented an argument for a toroidal field in the disk of IRc2. The results for Mon R2 and S140 IRS1, however, are unambiguous, and are indicative of magnetic fields lying parallel to the observed outflows. It must also be kept in mind that we are only looking at the absorptive component of the polarisation, and that this will be probing the cold dust presumably in the outer regions of the disk. Some of our objects also show an emissive component in their polarisation spectra. Such a component is due to warm dust which is lying closer to the source. The results for a few of these are quite interesting. As an example, the magnetic field component derived from the emissive polarisation toward NGC 7538 IRS1 is parallel to the large-scale CO bipolar outflow axis (whereas the absorptive component is parallel to the disk, e.g. Scoville *et al.* 1986), as is the case for IRc2.

5. Conclusions

A comparison between the magnetic field indicated by 10 μm polarisation, and that indicated by field stars, in 22 star formation regions, implies that there is some correlation between the two directions. This points to the importance of magnetic fields in the star formation process.

Further comparison with the axis directions of circumstellar disks and bipolar outflows indicates that, at least in the outer cool parts of the disk, the magnetic field takes on a toroidal geometry. This could be due to an initially poloidal field being wound up in the disk by rotation.

A more detailed analysis of the above relations will be presented in a following paper.

Acknowledgments

I would like to thank Prof. A. R. Hyland for providing financial assistance through a Physics Department Scholarship at the Australian Defence Force Academy.

References

Aitken, D.K. (1989). Proc. 22nd Eslab Conf. on Infrared Spectroscopy in Astronomy (Ed. B.H. Kaldeich), p. 99 (ESA Publications Division: Noordwijk).

Aitken, D.K. (1992). *Aust. J. Phys.* **45**, 569.

Aitken, D.K., Bailey, J.A., Roche, P.F., and Hough, J.H. (1985). *Mon. Not. R. Astron. Soc.* **215**, 813.

Aitken, D.K., Roche, P.F., Smith, C.H., James, S. D., and Hough, J. H. (1988). *Mon. Not. R. Astron. Soc.* **230**, 629.

Axon, D. J., and Ellis, R. S. (1976). *Mon. Not. R. Astron. Soc.* **177**, 499.

Bally, J., and Lada, C. J. (1983). *Astrophys. J.* **265**, 824.

Bastien, P., and Menard, F. (1988). *Astrophys. J.* **326**, 334.

Bastien, P., and Menard, F. (1990). *Astrophys. J.* **364**, 232.

Dyck, H. M., and Lonsdale, C. J. (1979). *Astron. J.* **84**, 1339.

Dyck, H. M., and Lonsdale, C. J. (1981). *In* 'Infrared Astronomy', IAU Symp. No. 96. (Eds C. G. Wynn-Williams and D. P. Cruikshank), p. 223 (Reidel: Dordrecht).
Fukui, Y. (1989). ESO Workshop on Low Mass Star Formation and Pre-Main Sequence Objects, preprint.
Hayashi, M., Hasegawa, T., Omodaka, T., Hayashi, S. S. and Miyawaki, R. (1987). *Astrophys. J.* **312**, 327.
Heckert, P.A., and Zeilik, M., II (1981). *Astron. J.* **86**, 1076.
Hodapp, K.-W. (1984). *Astron. Astrophys.* **141**, 255.
Kawabe, R., Ogawa, H., Fukui, Y., Takano, T., Takaba, H., Fujimoto, Y., Sugitani, K., and Fujimoto, M. (1984). *Astrophys. J. (Lett.)*, **282**, L73.
Lada, C. J. (1985). *Annu. Rev. Astron. Astrophys.* **23**, 267.
Martin, P. G. (1975). *Astrophys. J.* **202**, 393.
Minchin, N. R., Hough, J. H., McCall, A., Burton, M. G., McCaughrean, M. J., Aspin, C., Bailey, J. A., Axon, D. J., and Sato, S. (1991*a*). *Mon. Not. R. Astron. Soc.* **248**, 715.
Minchin, N. R., Hough, J. H., McCall, A., Aspin, C., Hayashi, S. S., Yamashita, T., and Burton, M. G. (1991*b*). *Mon. Not. R. Astron. Soc.* **251**, 508.
Minchin, N. R., Hough, J. H., Burton, M. G., and Yamashita, T. (1991*c*). *Mon. Not. R. Astron. Soc.* **251**, 522.
Mitchell, G. F., Maillard, J.-P., and Hasegawa, T. I. (1991). *Astrophys. J.* **371**, 342.
Plambeck, R. L., Wright, M. C. H., Welch, W. J., Bieging, J. H., Baud, B., Ho, P. T. P., and Vogel, S. N. (1982). *Astrophys. J.* **259**, 617.
Pudritz, R. E. (1985). *Astrophys. J.* **293**, 216.
Pudritz, R. E., and Norman, C. A. (1983). *Astrophys. J.* **274**, 677.
Pudritz, R. E., and Norman, C. A. (1986). *Astrophys. J.* **301**, 571.
Sandell, G. (1989). *In* 'Structure and Dynamics of the Interstellar Medium', IAU Colloq. No. 120 (Eds G. Tenorio-Tagle *et al.*), p. 244 (Springer: Berlin).
Sato, S., Nagata, T., Nakajima, T., Nishida, M., Tanaka, M., and Yamashita, T. (1985). *Astrophys. J.* **291**, 708.
Scoville, N. Z., Sargent, A. I., Sanders, D. B., Claussen, M. J., Masson, C. R., Lo, K. Y., and Phillips, T. G. (1986). *Astrophys. J.* **303**, 416.
Snell, R. L., Scoville, N. Z., Sanders, D. B., and Erickson, N. R. (1984). *Astrophys. J.* **284**, 176.
Takano, T., Fukui, Y., Ogawa, H., Takaba, H., Kawabe, R., Fujimoto, Y., Sugitani, K., and Fujimoto, M. (1984). *Astrophys. J. (Lett.)*, **282**, L69.
Torrelles, J. M., Rodriguez, L. F., Canto, J., Carral, P., Marcaide, J., Moran, J. M., and Ho, P. T. P. (1983). *Astrophys. J.* **274**, 214.
Walker, C. K., Adams, F. C., and Lada, C. J. (1990). *Astrophys. J.* **349**, 515.
Wolf, G. A., Lada, C. J., and Bally, J. (1990). *Astron. J.* **100**, 1892.

Manuscript received 13 November 1991, accepted 30 January 1992