The massive star-forming region G323.74–0.26

A. J. Walsh,^{1★†} J.-K. Lee² and M. G. Burton²

¹Max-Planck-Institut für Radioastronomie, auf dem Hügel 69, D-53121, Bonn, Germany

²Department of Astrophysics and Optics, School of Physics, University of New South Wales, NSW 2052, Australia

Accepted 2001 September 24. Received 2001 August 3; in original form 2001 June 22

ABSTRACT

We report near-infrared molecular hydrogen and Brackett γ observations towards the massive star formation site G323.74–0.26. The region contains an H II region, ~ 30 arcsec across, and two Class II methanol maser sites, which are separate from the H II region. We show that the spectral type of the star powering the H II region is B0. We also show that at least one of the maser sites is powered by an infrared source that appears to be at least as luminous as the star responsible for the H II region. However, neither of the two stars associated with the methanol maser sites shows any signs of radio continuum emission above 0.2 mJy. For at least one of these maser sites, this shows a real deficiency in the radio continuum flux, which we suggest is an indication that the star is in an early stage of development, before its H II region becomes visible, or it is a multiple intermediate mass star system. A shocked molecular hydrogen outflow is seen extending from one of the maser sites towards the west and possibly in a fan shape, suggesting that the stars associated with the maser sites are indeed at a very early stage of evolution.

Key words: masers – stars: formation – H II regions – ISM: individual: G323.74–0.26 – ISM: jets and outflows.

1 INTRODUCTION

Massive stars are an important constituent of the star formation process. They have a profound effect on the interstellar medium by way of their energy and momentum outputs. They dominate the circulation of heavy elements, and they trace the rate of star formation throughout the history of the Universe. Unravelling the initial conditions for, and the processes accompanying their formation remains one of the great challenges in modern astrophysics.

While detailed observations have revealed much insight to the genesis of low-mass stars, the process of massive star formation has remained more obscure for a number of reasons. Massive stars are rarer and thereby more distant. They form very quickly, thus providing only a sparse sample of objects representing the various evolutionary stages. In releasing large amounts of energy in radiation, winds and jets, young massive stars quickly alter their environment, and thereby destroy traces of the conditions under which they were able to form.

The most prominent tracers of young massive stars are compact, or ultracompact H II (UC H II) regions. Their radio emission is detectable throughout the Galaxy, and extensive surveys have been conducted to locate them (Wood & Churchwell 1989; Becker et al.

1994). Masers were also recognized to trace young, massive star-forming regions (e.g. Menten 1991; Forster & Caswell 1989). While H₂O and OH masers are also found towards other astrophysical objects such as the circumstellar envelopes of late-type stars (e.g. Wilson & Barrett 1972) and the centres of galaxies (e.g. dos Santos & Lepine 1979), the 6.7-GHz methanol (CH₃OH) maser line emission appears to be closely correlated with massive star-forming regions (Walsh et al. 1997). Apparently, only the most massive stars give rise to sufficiently strong far-infrared radiation to pump the methanol maser.

We have previously reported near-infrared (NIR) molecular hydrogen (H₂) observations towards a small sample of methanol maser sources (Lee et al. 2001). One complex and interesting region that was discovered is G323.74–0.26 (referred to as IRAS 15278-5620 by Lee et al.). This region forms the focus of this work.

6.7-GHz methanol (MacLeod, Gaylard & Nicholson 1992; Norris et al. 1993), 12.2-GHz methanol (Kemball, Gaylard & Nicholson 1988; Caswell et al. 1993; Caswell, Vaile & Forster 1995), 107-GHz methanol (Val'tts et al. 1999), 1.665 and 1.667-GHz OH (Caswell 1998) and 22.2-GHz H₂O (Scalise, Rodriguez & Mendoza-Torres 1989) maser emission have been detected towards this region. High spatial resolution images of 6.7-GHz methanol maser emission show a complex morphology (Norris et al. 1993), with two sites of emission (Phillips et al. 1998; Walsh et al. 1998) separated by 5 arcsec. Phillips et al. (1998) show that the western maser site (hereafter referred to as MMW, the

★E-mail: awalsh@cfa.harvard.edu

†Present address: Harvard-Smithsonian Center for Astrophysics, Mail Stop 42, 60 Garden Street, Cambridge, MA 02138, USA.

Figure 1. Infrared images of G323.74–0.26: (a) $H_2(1-0)$ at $2.12 \mu\text{m}$ showing the positions of the two methanol maser sites MME and MMW as plus symbols; (b) $H_2(2-1)$ at $2.25 \mu\text{m}$; (c) $\text{Br}\gamma$ at $2.16 \mu\text{m}$; (d) grey-scale, K -band at $2.2 \mu\text{m}$ (Walsh et al. 1999) and contours are 8.64-GHz radio continuum emission (Phillips 2000); (e) the grey-scale is as in (d) and the contours are MSX 21- μm emission. The ellipse traces the $IRAS$ error ellipse; (f) the grey-scale is as in (d) and the contours are 10.5- μm emission (Walsh et al. 2001). Note that the scale for (f) is different from the others.

other maser site is hereafter referred to as MME) has a linear morphology. NIR broad-band images of this region (Walsh et al. 1999) show two bright, red sources at $3.6\,\mu\text{m}$, with $K - L > 2.5$ mag, coincident with the two methanol maser sites.

Recent results by Lee et al. (2001) show extensive H_2 2.12- μm emission: the H_2 emission appears to extend away from the maser sites to the NW, in a fan shape. This H_2 emission is highly blueshifted, with respect to the maser radial velocity ($\sim 35\,\text{km s}^{-1}$). Faint redshifted emission is also seen on the opposite side of the maser sites. This leads to the conclusion that the H_2 emission is tracing a bipolar outflow.

Extended K -band (2.2- μm) emission is seen to the north of the maser sites that does not correspond to H_2 emission at $2.12\,\mu\text{m}$. The emission is coincident with an extended H II region (Phillips et al. 1998) (hereafter referred to as G323H II).

2 NIR FABRY-PEROT OBSERVATIONS

G323.74–0.26 was observed in 1–0 S(1) and 2–1 S(1) transitions of H_2 and $\text{Br}\gamma$ line emission on 1999 June 25. The University of New South Wales Infrared Fabry–Perot (FP) (UNSWIRF; Ryder et al. 1998) on the 3.9-m Anglo-Australian Telescope (AAT) was used in conjunction with the 128×128 pixel² Infrared Imager and Spectrometer (IRIS; Allen et al. 1993). The UNSWIRF is a narrow-band ($\lambda/\delta\lambda \sim 4000$) tunable filter for the NIR, and used at $f/36$ it produces a circular image of 100-arcsec diameter with a pixel scale of 0.8 arcsec. The velocity resolution is $75\,\text{km s}^{-1}$ FWHM.

The observing sequence with UNSWIRF included one off-line setting (for continuum subtraction) and several on-line FP spacings equally spaced about the line centre, determined by the maser radial velocities. Five on-line spacings were used for 1–0 S(1) and $\text{Br}\gamma$ line emission, and four spacings for 2–1 S(1) line emission. This sequence was carried out with a 3-min integration time for each FP spacing, first on the source and then on a sky position for sky subtraction. A standard star was imaged at each of the FP settings, as was a dome lamp to obtain a flat-field. The line flux and central velocities for the emission were determined through Lorentzian fitting of the data along the velocity axis. The fitting gives ~ 30 per cent error in the absolute flux measurement, and the absolute velocity can be measured within $15\text{--}20\,\text{km s}^{-1}$ accuracy, based on comparison with that of known H_2 emitting sources. Relative velocity differences $\geq 10\,\text{km s}^{-1}$ in a source can be discerned. The data were reduced with a customized reduction package using IRAF routines. We estimate rms noise levels for the $\text{H}_2(1\text{--}0)$, $\text{H}_2(2\text{--}1)$ and $\text{Br}\gamma$ images to be 0.69×10^{-16} , 0.64×10^{-16} and $1.0 \times 10^{-16}\,\text{erg cm}^{-2}\,\text{s}^{-1}\,\text{arcsec}^{-2}$, respectively.

3 RESULTS

The $\text{H}_2(1\text{--}0)$ line emission has previously been presented (Lee et al. 2001). However, we reproduce the results here for comparison with the other line and continuum emission: namely, $\text{H}_2(1\text{--}0)$ and (2–1) emission, $\text{Br}\gamma$ emission, broad-band K emission, 8.64-GHz radio continuum emission, mid-infrared (MIR) 21- μm emission, as observed by the *Midcourse Space Experiment*¹ (MSX), and MIR 10.5- μm emission (Walsh et al. 2001), shown in Fig. 1.

The H_2 emission in both lines is seen to extend over most of the field of view (Figs 1a and b). One main component is the strong

line emission to the west of the maser sites. This line emission was shown to be highly blueshifted by Lee et al. (2001). Line emission is also strong at the position of MME, and occurs at MMW, although it is much fainter. H_2 line emission to the SE of the maser sites, which Lee et al. show is redshifted with respect to the maser radial velocities. H_2 line emission is also seen to the NW of the field of view. It appears to surround G323H II.

The $\text{Br}\gamma$ image in Fig. 1(c) clearly shows a bright, presumably spherical H II region (G323H II), to the NW of the image. Comparison with the NIR K -band image (Walsh et al. 1999) and overlaid 8.64-GHz radio continuum image (Phillips 1998), shown in Fig. 1(d), indicates that the $\text{Br}\gamma$ emission coincides with radio continuum emission mapped by Phillips et al. (1998), although the $\text{Br}\gamma$ emission appears to be more extensive. There is a bright star located close to the centre of G323H II [coordinates: $15^{\text{h}}31^{\text{m}}44^{\text{s}}.3$, $-56^{\circ}30'16''$ (J2000)], shown in the K -band (2.2- μm) image of Fig. 1(d), which is probably the exciting star of the H II region.

Recently released 21- μm data from the *MSX* are shown in Fig. 1(e). With a higher resolution than *IRAS*, we see two dominant IR sources in the field. One is associated with G323H II and the other with the maser site(s). From the higher-resolution MANIAC data (Walsh et al. 2001) shown in Fig. 1(f), it is clear that the *MSX* source at the maser sites is composed of two IR sources, coincident with MMW and MME. One of these IR sources is not seen at $2.2\,\mu\text{m}$, but only at longer wavelengths (MMW), suggesting that it is very deeply embedded. Weak $\text{Br}\gamma$ emission appears associated with the other maser site, MME.

4 DISCUSSION

4.1 Spectral type of G323H II powering source

For G323H II, the spectral type for the exciting star can be derived, based on the radio continuum flux ($123.3\,\text{mJy}$; Phillips et al. 1998), using equation (4) of Kurtz et al. (1994). The number of ionizing photons per second is 1.5×10^{47} , corresponding to a B0-type star. We can now compare this with the spectral type derived from our $\text{Br}\gamma$ measurements. The number of ionizing photons from the exciting star can be derived using equation (1) (Ho, Beck & Turner 1990):

$$N_L = 2.9 \times 10^{45}\,\text{s}^{-1} \left(\frac{N_L/N_{\text{Br}\gamma}}{11.8} \right) \times \left(\frac{D}{\text{kpc}} \right)^2 \left(\frac{S_{\text{Br}\gamma}}{10^{-12}\,\text{erg s}^{-1}\,\text{cm}^{-2}} \right), \quad (1)$$

where $N_L/N_{\text{Br}\gamma} = 13.2$ and $S_{\text{Br}\gamma} = 2.82 S_{\text{Br}\gamma}$, equivalent to assuming an electron temperature of $10^4\,\text{K}$ and density of $10^4\,\text{cm}^{-3}$. With an integrated $\text{Br}\gamma$ flux of $1.39 \times 10^{-12}\,\text{erg s}^{-1}\,\text{cm}^{-2}$ and an assumed distance of 3.6 kpc, we expect 1.64×10^{47} ionizing photons per second. This corresponds to a bolometric luminosity of $2.5 \times 10^4 L_{\odot}$, equivalent to a B0 zero-age main-sequence (ZAMS) star (Thompson 1984). This is similar to the luminosity derived using the radio continuum flux and gives us confidence in assigning a spectral type of B0 to the exciting star.

The extinction to the region can be calculated by comparing the $\text{Br}\gamma$ and radio continuum fluxes. This is based on the assumption that the radio flux is not significantly affected by extinction, but the $\text{Br}\gamma$ flux is. The radio and $\text{Br}\gamma$ fluxes imply similar numbers of ionizing photons per second. This may mean that there is no significant extinction towards this region, however, since the radio continuum emission was mapped by the Australia Telescope

¹ Available at <http://www.ipac.caltech.edu/ipac/msx/msx.html>

Compact Array (ATCA), a synthesis imaging telescope, there may be extended emission present that was resolved out with the telescope. This appears to be the case: by comparing the sizes of the Br γ and radio continuum emission shown in Fig. 1 – the Br γ is clearly more extended. Thus, the ATCA measurements by Phillips et al. (1998) almost certainly underestimate the true radio flux of G323H II.

To recover any missing emission, single-dish data are required. Such data are provided by the Parkes–MIT–NRAO (PMN; Wright et al. 1994) survey. The PMN point source PMN J1531-5630 coincides with G323H II. It has an integrated flux of 312 mJy at 4.85 GHz. This is larger than the flux detected by Phillips et al. (1998): 0.123 Jy at 8.64 GHz. We expect such a large H II region to be optically thin at 4.85 and 8.64 GHz, therefore we expect the fluxes to be approximately equal at these frequencies. Since they are different, this could be either because of missing extended emission in the ATCA data, or because of confusion of the PMN source. Confusion is likely because the large beam of the PMN survey (4.2-arcmin FWHM) may include emission from other nearby radio sources. Therefore, we treat the PMN flux as an absolute upper limit to the radio flux of G323H II. Using this PMN flux we predict the Br γ flux to be $2.8 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$, and so we find an upper limit on the extinction to the H II region, by comparing the predicted and observed Br γ fluxes, as in equation (2) (Howard, Pipher & Frost 1994):

$$F_{\lambda}^{\text{observed}} = F_{\lambda}^{\text{predicted}} \exp(-\tau_{\lambda}). \quad (2)$$

Since we consider the PMN flux as an upper limit on the H II region flux, we find $\tau_{2.16 \mu\text{m}} \leq 0.69$, equivalent to a visual extinction, $A_v \leq 8.9$.

4.2 Spectral type of MME powering source

Walsh et al. (2001) estimate that either a single star or star cluster, with the measured MIR fluxes for MME, should have a radio continuum flux between the extreme values of 0.23 mJy and 4.9 Jy, assuming a distance of 3.6 kpc. The most likely value corresponds to a single star of B0 spectral type. However, no radio continuum emission was detected above the 4σ value of 0.2 mJy at 8.6 GHz (Phillips et al. 1998). The extreme theoretical lower limit is higher than the measured upper limit, suggesting that there may be missing radio continuum flux from MME, but the closeness of the theoretical limit (0.23 mJy) and the measured limit (0.2 mJy) does not make for a strong case: further radio continuum observations are needed to search for a weak radio source here.

The above analysis has assumed that the emission comes from either one star or a cluster of stars with an initial mass function (IMF). However, it might be possible that the infrared emission from MME is dominated by a small number of intermediate mass stars (e.g. a binary or triple system). In this case, the combined luminosity of two companion stars of approximately equal mass may be sufficient to produce the observed infrared (IR) fluxes, but they would not produce enough ultraviolet (UV) photons to create observable radio continuum emission.

Br γ emission is seen close to MME (Fig. 1c). It is very weak emission with a flux of $5.3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$, equivalent to a 2σ detection. We favour the interpretation that it is real emission associated with MME since it is closely aligned with MME, but we do caution that this is a very weak detection. If this Br γ emission is real, it corresponds to a B2 star or earlier, depending on the extinction toward MME.

Perhaps the clearest case for a discrepancy between the bright MIR source and the lack of radio continuum emission is seen in comparison with G323H II. G323H II clearly has a well developed and bright H II region and yet the powering star has a similar flux in the NIR to the powering star of MME (Walsh et al. 1999). So, why do we not see a similar H II region around MME? Furthermore, the redder NIR colours of the star associated with MME than that associated with G323H II (Walsh et al. 1999) indicate that MME should be more luminous, producing an even brighter H II region. From this we conclude that MME is either a close multiple-star system or is in an earlier stage of evolution than G323H II, before the H II region has had chance to form.

4.3 Spectral type of MMW powering source

The MIR emission detected by Walsh et al. (2001) towards MMW has a similar flux to MME, although a little lower, implying the most likely spectral type (assuming a single star) is B0.5. We find the theoretical lower limit to the radio continuum flux, based on the MIR measurements, to be 0.15 mJy. Since this is below the 4σ detection limit, we do not have any conclusive evidence for missing radio continuum emission from this source.

The methanol maser site MMW shows no evidence of Br γ , or indeed any emission shortward of $3.6 \mu\text{m}$ (Walsh et al. 1999). Thus it seems likely that this is a very deeply embedded object. This is confirmed by the fact that no source is seen at this position shortward of $3.6 \mu\text{m}$, and yet the brightness of this source approaches that of the MIR source associated with MME at $20.0 \mu\text{m}$, implying a very steeply rising spectrum in the near- to mid-infrared for MMW.

4.4 H₂(1–0) and H₂(2–1)

Figs 1(a) and (b) show widespread emission from H₂ in the NIR. H₂ emission can either be triggered by UV photons, giving rise to fluorescence or by collisions occurring within shocks, presumably associated with an outflow. A good diagnostic to distinguish between these two causes is to measure the ratio of the (1–0) to (2–1) lines. A line ratio of 10 is expected from purely shock-excited emission, whereas a ratio of 2 is expected from purely fluorescent emission. We do not provide a line ratio image since we have found through experience that such images tend to be dominated by noise from areas of low line flux, and very slight misalignments of the H₂(1–0) and H₂(2–1) frames can lead to large differences in the line ratio in places. We have found the most reliable way to present line ratios is to average emission over small ($4 \times 4 \text{ arcsec}^2$) boxes. Thus, for various positions, shown in Fig. 2, the ratio of H₂(1–0) to H₂(2–1) line intensities is given in Table 1.

Boxes 9–17 all show line ratios of between 1.8 and 2.8, suggesting that the H₂ emission in these areas is fluorescent. The morphology of the H₂ emission, which includes these boxes appears as a shell wrapping around G323H II. This is expected for an H II region: the ionized region, traced by both the Br γ emission and the radio continuum emission (Figs 1c and d, respectively) is surrounded by heated gas, traced by the H₂ emission.

Boxes 1–8 have line ratios that lie between what would be expected for purely fluorescent and purely shock-excited emission, thus we consider both mechanisms to be acting to produce the observed emission in these regions. It is important to note that the ratios for boxes 1–8 are higher than the ratio for purely fluorescent emission, as this leads us to the conclusion that there must be shocked gas, and therefore an outflow, present. The morphology of

Figure 2. The H_2 (1–0) (left) and (2–1) (right) are reproduced from Figs 1(a) and (b), with boxes indicating positions where the line ratio was calculated.

Table 1. Details for each box shown in Fig. 2 are given. Column 1: the corresponding box number. Column 2: the integrated $H_2(1-0)$ line flux. Column 3: the average radial velocity of the line emission. Column 4: the $H_2(1-0)$ to (2–1) line ratio.

Box number	$H_2(1-0)$ line flux ^a (10^{-16} erg cm $^{-2}$ s $^{-1}$)	Radial velocity (km s $^{-1}$)	Line ratio
1	5.4	–48	7.9
2	7.0	–92	7.9
3	13	–81	5.9
4	8.1	–87	6.0
5	12	–86	3.1
6	4.5	–75	3.6
7	9.8	–83	3.0
8	9.0	–77	4.5
9	8.3	–80	2.1
10	8.0	–78	2.4
11	7.5	–83	2.4
12	8.1	–81	2.8
13	6.1	–75	2.5
14	4.4	–81	1.8
15	5.7	–62	2.1
16	6.0	–50	2.4
17	5.1	–45	2.6

^aIntegrated over each 4×4 arcsec 2 box.

the H_2 emission suggests that the outflow extends from one of the maser sites (it is not clear which) to the west.

Previously, Lee et al. (2001) interpreted the H_2 emission as showing a blueshifted fan-shaped outflow. The outflow, in comparison with this work, extends from one of the maser sites and includes boxes 4, 5, 7 and 9 for the lower edge of the fan, and boxes 10–12 and 14 for the upper edge of the fan. Lee et al. identified this structure based on the fact that it was blueshifted with respect to the H_2 emission seen elsewhere (e.g. boxes 15–17).

The kinematics of the region become clearer by comparing the line velocities given in column 3 of Table 1, which are reproduced

from the data of Lee et al. (2001). For comparison, we find the Bry line emission to occur between radial velocities of ~ -55 to -40 km s $^{-1}$. Thus, one would expect that boxes containing H_2 line emission with similar velocities to this are more likely to be from fluorescence, and H_2 emission with different velocities are more likely to be shock excited. Boxes 4, 5, 7 and 9 (the lower edge of the fan) have radial velocities of between ~ -90 and -80 km s $^{-1}$; boxes 10–12 and 14 (the upper edge of the fan) have radial velocities between ~ -85 and -75 km s $^{-1}$; boxes 15–17 (surrounding G323H II) show velocities of between ~ -65 and -45 km s $^{-1}$.

Our line ratio data suggest that the upper edge of the fan is dominated by fluorescently excited emission. However, the boxes contained within this region show the velocity of the emission is at least 20 km s $^{-1}$ blueshifted with respect to the velocity expected from the Bry emission. We consider this encouraging evidence that the H_2 emission in the upper edge of the fan is indeed shock excited. Nevertheless, the lack of line ratios indicative of shock-excited gas leads us to conclude that further data are needed to resolve whether a fan-shaped outflow or just an outflow to the west of the maser site(s) exists. Owing to the complicated nature we have discovered in this source, interferometric molecular line studies in outflow tracers such as CS and HCO^+ will be required to adequately separate all the components in order to map the outflow. In any case, this region shows an outflow, which is probably powered by the same source that is powering at least one of the maser sites, thus providing more evidence that methanol masers are signposts of one of the earliest stages of massive star formation.

5 SUMMARY AND CONCLUSIONS

We have investigated the massive star-forming region G323.74–0.26, using all available data and new observations of H_2 and Bry emission. The region contains three sources of interest.

- (i) G323H II. This H II region is well traced by the Bry emission

and radio continuum emission. A comparison of the two fluxes indicates relatively low extinction towards the region ($A_V \leq 8.9$). The star powering the H II region is seen at near- to mid-infrared wavelengths. The exciting star is likely to have a spectral type of B0. H₂ emission surrounding the H II region is seen to fluoresce, as would be expected from the warm gas surrounding such an ionized region.

(ii) MME. This methanol maser site is found to the south of G323H II, close to the other maser site MMW. It is coincident with a near- and mid-infrared source we assume to be the powering the maser emission. From the infrared data, the most likely spectral type of the star is B0. A small amount of Br γ emission is detected at this position. Also, no radio continuum emission has been detected at this position. It is not clear why there is less Br γ and radio continuum emission than G323H II, given the similar spectral types, but we suggest either that the H II region has not had time to form yet or that MME is a close intermediate mass multiple-star system.

(iii) MMW. This methanol maser site is located ~ 5 arcsec to the west of MME. It must be associated with a deeply embedded star, since the star is only seen at wavelengths of $3.6 \mu\text{m}$ and longer, and yet it has a brightness comparable to MME at wavelengths of $20 \mu\text{m}$.

Extended H₂ emission, seen throughout the field of view appears to consist of two components. One is the fluorescence associated with G323H II, but there is also a shocked component. Its morphology is not clear: it is either a fan-shaped outflow or an outflow running east to west, apparently coming from one of the methanol maser sites. We interpret this as clear evidence for an outflow coming from a massive star, signposted by one of the methanol maser sites.

ACKNOWLEDGMENTS

We would like to thank Michael C. B. Ashley and John W. V. Storey for help in installing and running UNSWIRF in conjunction with IRIS on the Anglo-Australian Telescope. We would also like to thank S. Lumsden for helpful comments that have greatly increased the quality of this paper.

REFERENCES

- Allen D. A. et al., 1993, *Publ. Astron. Soc. Aust.*, 10, 298
 Becker R. H., White R. L., Helfand D. J., Zoonematkermani S., 1994, *ApJS*, 91, 347
 Caswell J. L., Gardner F. F., Norris R. P., Wellington K. J., McCutcheon W. H., Peng R. S., 1993, *MNRAS*, 260, 425
 Caswell J. L., Vaile R. A., Forster J. R., 1995, *MNRAS*, 277, 210
 Caswell J. L., 1998, *MNRAS*, 297, 215
 dos Santos P. M., Lepine J. R. D., 1979, *Nat*, 278, 34
 Forster J. R., Caswell J. L., 1989, *A&A*, 213, 339
 Ho P. T. P., Beck S. C., Turner J. L., 1990, *ApJ*, 349, 57
 Howard E. M., Pipher J. L., Forrest W. J., 1994, *ApJ*, 425, 707
 Kembell A. J., Gaylard M. J., Nicholson G. D., 1988, *ApJ*, 331, 37
 Kurtz S., Churchwell E., Wood D. O. S., 1994, *ApJS*, 91, 659
 Lee J.-K., Walsh A. J., Burton M. G., Ashley M. C. B., 2001, *MNRAS*, 324, 1102
 MacLeod G. C., Gaylard M. J., Nicholson G. D., 1992, *MNRAS*, 254, 1
 Menten K. M., 1991, *ApJ*, 380, L75
 Norris R. P., Whiteoak J. B., Caswell J. L., Wieringa M. H., Gough R. G., 1993, *ApJ*, 412, 222
 Phillips C. J., Norris R. P., Ellingsen S. P., McCulloch P. M., 1998, *MNRAS*, 300, 1131
 Phillips C. J., 1998, PhD thesis, Univ. Tasmania, Australia
 Ryder S. D., Sun Y.-S., Ashley M. C. B., Burton M. G., Allen L. E., Storey J. W. V., 1998, *PASA*, 15, 228
 Scalise E., Rodriguez L. F., Mendoza-Torres E., 1989, *A&A*, 221, 105
 Thompson R. I., 1984, *ApJ*, 283, 165
 Val'ts I. E., Ellingsen S. P., Slysh V. I., Kalenskii S. V., Otrupcek R., Voronkov M. A., 1999, *MNRAS*, 310, 1077
 Walsh A. J., Hyland A. R., Robinson G., Burton M. G., 1997, *MNRAS*, 291, 261
 Walsh A. J., Burton M. G., Hyland A. R., Robinson G., 1998, *MNRAS*, 301, 640
 Walsh A. J., Burton M. G., Hyland A. R., Robinson G., 1999, *MNRAS*, 309, 905
 Walsh A. J., Bertoldi F., Burton M. G., Nikola T., 2001, *MNRAS*, 326, 36
 Wright A. E., Griffith M. R., Burke B. F., Ekers R. D., 1994, *ApJS*, 91, 111
 Wilson W. J., Barrett A. H., 1972, *A&A*, 17, 385
 Wood D. O. S., Churchwell E., 1989, *ApJ*, 340, 265

This paper has been typeset from a $\text{\LaTeX}$ file prepared by the author.