Massive young stellar objects in the Large Magellanic Cloud: water masers and ESO-VLT 3–4 μm spectroscopy

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Accepted 2006 August 18. Received 2006 July 28; in original form 2006 June 5

ABSTRACT

We investigate the conditions of star formation in the Large Magellanic Cloud (LMC). We have conducted a survey for water maser emission arising from massive young stellar objects in the 30 Doradus region (N 157) and several other H II regions in the LMC (N 105 A, N 113 and N 160 A). We have identified a new maser source in 30 Dor at the systemic velocity of the LMC. We have obtained 3–4 μm spectra, with the European Southern Observatory (ESO)-Very Large Telescope (VLT), of two candidate young stellar objects. N 105 A IRS 1 shows H recombination line emission, and its Spectral Energy Distribution (SED) and mid-infrared colours are consistent with a massive young star ionizing the molecular cloud. N 157 B IRS 1 is identified as an embedded young object, based on its SED and a tentative detection of water ice. The data on these four HII regions are combined with mid-infrared archival images from the Spitzer Space Telescope to study the location and nature of the embedded massive young stellar objects and signatures of stellar feedback. Our analysis of 30 Dor, N 113 and N 160 A confirms the picture that the feedback from the massive O- and B-type stars, which creates the H II regions, also triggers further star formation on the interfaces of the ionized gas and the surrounding molecular cloud. Although in the dense cloud N 105 A star formation seems to occur without evidence of massive star feedback, the general conditions in the LMC seem favourable for sequential star formation as a result of feedback. In an Appendix, we present water maser observations of the galactic red giants R Doradus and W Hydrae.

Key words: masers – stars: formation – stars: pre-main-sequence – H II regions – Magellanic Clouds – infrared: stars.

1 INTRODUCTION

One of the great unknowns in our understanding of star formation concerns the role played by galactic environmental parameters. For instance, molecular cloud processes, for example cooling and magnetic field diffusion, depend on the presence of metals, thus it is unlikely that star formation is not affected by metallicity. The Magellanic Clouds have metallicity and density of the interstellar media (ISM) that are lower than in the Milky Way. Thus, they provide a star formation template that is more representative of the formation of stars at zero metallicity.

Young pre-main-sequence populations have recently been identified in H II regions in the Magellanic Clouds (Gouliermis et al. 2006; Nota et al. 2006). However, relatively little work has been done in investigating the earlier, more embedded stages of star formation in the Magellanic Clouds. At the distance of the Large Magellanic Cloud (LMC, ~50 kpc), one is limited to study only the most massive stellar embryos that will form massive O and B stars. Infrared (IR) observations are an excellent way to investigate the properties of such objects, because they are both heavily embedded and thus invisible at shorter wavelengths and surrounded by dense envelopes of gas, dust and ices that are revealed at these wavelengths (van Dishoeck 2004). Recently, a few massive young stellar objects (YSOs) in the LMC have been investigated (Jones et al. 2005; van Loon et al. 2005b).

Molecular masers (in particular water, hydroxyl and methanol) are very bright emission lines that seem to be closely associated with the earliest stages of massive star formation (de Buizer et al. 2005) when the YSOs are difficult to detect even at IR wavelengths. Maser emission is found in the vicinity of embedded YSOs and thus they are powerful beacons of current star formation in a molecular cloud. Several water maser sources have been discovered in the Magellanic Clouds (see below). In this contribution, we describe a new survey investigating the earlier, more embedded stages of star formation in the Magellanic Clouds. At the distance of the Large Magellanic Cloud (LMC, ~50 kpc), one is limited to study only the most massive stellar embryos that will form massive O and B stars. Infrared (IR) observations are an excellent way to investigate the properties of such objects, because they are both heavily embedded and thus invisible at shorter wavelengths and surrounded by dense envelopes of gas, dust and ices that are revealed at these wavelengths (van Dishoeck 2004). Recently, a few massive young stellar objects (YSOs) in the LMC have been investigated (Jones et al. 2005; van Loon et al. 2005b).

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of water maser sources in the LMC at 22 GHz with the Parkes Telescope.

In recent years, the 30 Doradus Nebula (N157) has become the paradigm of large-scale triggered star formation. As the largest and nearest extragalactic H ii region in the Local Group, it offers a rare insight into the spatial and temporal properties of starbursts. Walborn et al. (1999) identified the so-called star formation fronts, the interfaces between the energetic outflows from the central compact cluster R 136 (first-generation star formation episode) and the surrounding molecular clouds, in which there is evidence of ongoing triggered star formation. Water maser emission has also been detected at various locations in 30 Dor (Whiteoak et al. 1983; van Loon & Zijlstra 2001a; Lazendic et al. 2002). The wealth of bright protostars identified in the region (Rubio et al. 1998; Brandner et al. 2001) hints at the possibility that more masing activity hitherto undetected might be present. We describe our mapping survey of the inner region of 30 Dor, in which we have identified four distinct maser sources, one of them new.

Three other H ii regions in the LMC, known to show water maser emission (N 113, N 105A and N 160A; Whiteoak et al. 1983; Whiteoak & Gardner 1986) are also observed at 22 GHz, as well as most of the previous non-detections for water maser emission in the LMC and Small Magellanic Cloud (SMC; Scalise & Braz 1982; Whiteoak et al. 1983). Since our observations, Lazendic et al. (2002) also reported 22 GHz water maser emission towards N 159.

The H ii region N 113 (Henize 1956) shows a complex structure of H ii bubbles with a rich molecular gas and dust morphology. Several young clusters are associated with N 113 (Bica, Claria & Dottori 1992), and current star formation activity is occurring within continuum sources in the central area of the nebula (Brooks & Whiteoak 1997; Wong et al. 2006). The H ii region N 105 (Henize 1956) is a complex of evacuated bubbles and dense molecular material with several young clusters associated with it (Ambrocio-Cruz et al. 1998); current star formation as indicated by maser activity seems to concentrate in the denser central part of the region, N 105A. N 160A is the brightest component in the N 160 H ii complex (Henize 1956). Besides maser emission, both an embedded protostar (Henning et al. 1998) and a dense molecular core (Bolatto et al. 2000) point at ongoing star formation. Heydari-Malayeri et al. (2002) and Nakajima et al. (2005) describe the gas morphology and stellar content of N 160.

In order to investigate the relationship between the masers and the gas kinematics and star formation activity, we have obtained narrow-band Hα images at the Anglo-Australian Telescope (AAT) of N 113, and L’-band images and 3–4 μm spectroscopy at the European Southern Observatory (ESO)-Very Large Telescope (VLT) in N 157B and N 105A. These new observations, combined with archival Infrared Array Camera (IRAC)/Spitzer images, are used to relate the embedded population to the local gas and dust morphology.

### Table 1. Overview of the new data on the H ii regions discussed in detail in this paper.

| H ii region | 22 GHz | Hα image | L’ image | Spitzer 8-μm image | L-band spectrum | IR SED |
|-------------|--------|----------|---------|-------------------|----------------|-------|
| 30Dor (N 157A) | Map | | | + | IRS1 | IRS1 |
| N 157B | Single pointing | + | + | | IRS1 | |
| N 113 | Sparse map | + | | | | |
| N 105A | Single pointing | + | + | IRS1, Blob | IRS1 |
| N 160A | Single pointing | | + | | | |

2 OBSERVATIONS

The new observations used in this paper are described in this section, and a summary is given in Table 1.

2.1 The 22-GHz survey at Parkes

The 64-m radio telescope (effective diameter of 45 m) at Parkes, Australia, was used from 2001 June 30 to July 9, with the K-band (1.4 cm) receiver plus autocorrelator back-end to observe the 616 → 523 rotational transition of ortho-H$_2$O at a rest frequency of 22.235 079 85 GHz. The observations were performed at ~22.216 GHz yielding a velocity coverage of ~860 km s$^{-1}$ with 0.42 km s$^{-1}$ channel$^{-1}$. Using the dual circular feed, spectra were obtained simultaneously in left and right circular polarization; these were then averaged.

The system temperature varied between 120 and 140 K. The conversion factor from antenna temperature to flux density was 6 Jy K$^{-1}$. Observing conditions were sometimes rather unstable due to clouds. The on-source integration time was 20 min per pointing.

The pointing and focus were checked regularly by observing the bright maser sources R Doradus and W Hydrae (see Appendix B). The absolute flux calibration is accurate to ~20 per cent.

The obtained spectra were corrected for two distinct baseline effects: a low-frequency feature (easily removed with a third-degree polynomial) and an interference signal with a frequency of ~2.85 MHz. The shape of this interference was re-constructed by median averaging the cycles within each spectrum, and was then subtracted from the spectrum.

The observations in the central area of 30 Dor (LHA 120-N 157A) were performed on a double grid system (x, y): the primary grid has a separation of one beam, that is, 1.3 arcmin; the secondary grid positions are obtained by shifting the primary grid positions by 39 arcsec in right ascension and declination. We performed 58 pointings at 47 distinct positions around R 136 (some positions deemed interesting were observed twice), covering a 5 × 5 arcmin$^2$ area. The pointings are shown in Fig. 1, superimposed on a Midcourse Space Experiment (MSX) 8-μm image. An extra pointing was performed on N 157B, but note that it is offset by 1 arcmin from the peak emission in the mid-IR.

The observations of N 113 were performed in a five-position dither pattern with 39-arcsec shifts. Single pointings were performed towards a number of other H ii regions; maser sources were detected towards N 105A and N 160A, while for 11 other regions no masing source was detected (see Appendix A).

2.2 The 3–4 μm observations at the VLT

The Infrared Spectrometer And Array Camera (ISAAC) on the ESO-VLT, Chile, was used on 2003 December 7 and 8 to obtain...
long-slit spectra between 2.85 and 4.15 \(\mu\)m of two candidate embedded YSOs. MSX LMC 888 (hereafter N 157B IRS1) (Egan, van Dyk & Price 2001) is located in the 30 Dor region and was selected based on its very red colours (consistent with a massive YSO) while MSX LMC 80 (N 105A IRS1) is a candidate protostar first identified by Epchtein, Braz & Sêvre (1984) (see Section 3.2 for a complete discussion on these sources).

The resolving power of \(\lambda/\Delta \lambda \sim 700\) was set by the ~0.5 arcsec seeing rather than the 2-arcsec slit width. The thermal-IR technique of chopping and nodding was used to remove the background, with a throw of 10 arcsec, jittering within 2 arcsec to correct for bad pixels.

Total exposure times were 12 min. The images were obtained in chopping-only mode, with a throw of 10 arcsec in the north–south direction. The total exposure times were 12 min. The spectra were extracted using each image received an integration time of 1 min, and a total of six such cycles were performed before CCD read-out. This was repeated with images taken at \(\lambda_0 + 3\Delta \lambda/2\), \(\lambda_0 + \Delta \lambda/2\) and \(\lambda_0 - \Delta \lambda/2\), respectively, to improve the spatial and spectral sampling of \(H\alpha\) as the instrument is placed in the pupil the wavelength changes with radial distance \(r\) in pixels as (cf. Bland & Tully 1989)

\[
\frac{\lambda}{\lambda_0} = 1 - \frac{r^2}{2} \left( \frac{p}{f} \right)^2,
\]

where \(p = 13.5\ \mu\)m is the pixel size and \(f = 127.8\) mm is the camera focal length.

The data were corrected for bias offset and divided by a flat-field image. For each of the two pointings, the images were combined to produce one image corresponding to the \(H\alpha\) line emission and another image corresponding to the underlying continuum emission. This was done on a pixel-by-pixel basis by assuming that the \(H\alpha\) emission has a Gaussian spectral shape with a full width at half-maximum of 7 \(\AA\), and that the continuum is flat. The resulting \(H\alpha\) image is very clean with most stars removed.

2.4 Additional IR data

Near-IR \(H\) and \(K\) photometry is taken from the Two-Micron All-Sky Survey (2MASS; Cutri et al. 2003). Embedded massive stars have very red \(J - K\) colours; thus, at the distance of the Magellanic Cloud, the photometric accuracy is of the order of 0.1–0.2 mag, found from cross-correlation of acquisition images of other targets in the same observing run with dedicated \(L\)-band photometry (van Loon, Marshall & Zijlstra 2005a).

2.3 The \(H\alpha\) mapping at the AAT

The Taurus Tunable Filter instrument on the AAT, Australia, was used on 2001 July 17 to obtain narrow-band \(H\alpha\) images of N 113. The blue etalon was used in combination with the EEV CCD, at a spectral resolution of \(\Delta \lambda \sim 7\) \(\AA\) around \(H\alpha\). The central wavelength was set to \(\lambda_0 = 6568\ \AA\), corresponding to a Doppler shift similar to that of the LMC. The technique of charge shuffling was applied to take a series of three consecutive images before reading out the CCD, where each image was taken on the same area of the CCD but at a central wavelength of \(\lambda_0 + \Delta \lambda\), \(\lambda_0\) and \(\lambda_0 - \Delta \lambda\), respectively. Each image received an integration time of 1 min, and a total of six such cycles were performed before CCD read-out. This was repeated with images taken at \(\lambda_0 + 3\Delta \lambda/2\), \(\lambda_0 + \Delta \lambda/2\) and \(\lambda_0 - \Delta \lambda/2\), respectively, to improve the spatial and spectral sampling of \(H\alpha\); as the instrument is placed in the pupil the wavelength changes with radial distance \(r\) in pixels as (cf. Bland & Tully 1989)

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\frac{\lambda}{\lambda_0} = 1 - \frac{r^2}{2} \left( \frac{p}{f} \right)^2,
\]

where \(p = 13.5\ \mu\)m is the pixel size and \(f = 127.8\) mm is the camera focal length. The two sets of observations were repeated with an offset of 1 arcmin in the north–south direction to cover more of N 113. The observations were made at a distance of 50\(^\circ\) from the zenith and a seeing of 1.8 arcsec.

The data were corrected for bias offset and divided by a flat-field image. For each of the two pointings, the images were combined to produce one image corresponding to the \(H\alpha\) line emission and another image corresponding to the underlying continuum emission. This was done on a pixel-by-pixel basis by assuming that the \(H\alpha\) emission has a Gaussian spectral shape with a full width at half-maximum of 7 \(\AA\), and that the continuum is flat. The resulting \(H\alpha\) image is very clean with most stars removed. The main \(H\alpha\) emission structures are so strong that they are still present in the ‘continuum’ image, albeit at a much lower level (Section 3.4).
Clouds, most embedded YSOs are only detected by 2MASS in the K_s band. Hence, bright K_s-band sources with faint or undetected shorter wavelength counterparts in 2MASS are embedded YSO candidates.

For the two luminous IR objects, N 157B IRS1 and N 105A IRS1 (Section 3.2), mid-IR photometry at 8.28, 12.1, 14.7 and 21.3 μm is taken from version 2.3 of the MSX Point Source Catalogue (Egan et al. 2003). The spatial resolution of these data varies from 7 arcsec at 8.28 μm to 18 arcsec at 21.3 μm. We also collected scans from the IRAS data server3 for these two sources, to measure their 12, 25, 60 and 100 μm flux densities using the Groningen Image Processing System (GIPSYS) software with the SCANAID tool. These measurements were fully consistent with the IRAS Point Source Catalogue (PSC; Beichman et al. 1988), but contrary to the PSC we were able to obtain a measurement for N 157B IRS1 also at 60 and 100 μm. In addition, for N 105A IRS1 we inspected Low-Resolution Spectrograph scans from the IRAS data server. The three complete scans are fully consistent with each other, and show a weak depression around 10 μm which could be indicative of absorption by silicate dust. The mid-IR photometry helps constrain the luminosity and hence the mass of the star.

In our analysis of the morphology of the 4 H II regions, we also made use of archival images obtained with the Spitzer Space Telescope (Werner et al. 2004), using IRAC (Fazio et al. 2004). IRAC images of 30 Dor were obtained under Early Release Observation programme 1032 (P.I. B. Brandl). Both N 105A and N 113 observations are part of the cycle 2 Legacy programme 20203 (P. I. M. Meixner) while the N 160A observations are part of the Guaranteed Time Observations programme 124 (P.I. R. Gehrz). Extended pipeline products (i.e. flux-calibrated image mosaics) for the four IRAC bands (3.6, 4.5, 5.8 and 8.0 μm) were retrieved from the Spitzer archive.2 We have performed aperture photometry on the IRAC mosaics, for the sources present in the L′ acquisition images. We performed aperture corrections but not array-location-dependent corrections or colour corrections (Reach et al. 2005), so fluxes might be uncertain by as much as 10 per cent, still fully adequate for our analysis (see Section 3.3).

3 RESULTS

3.1 22-GHz survey

3.1.1 Mapping of 30 Dor (N 157)

The goal of the 30 Dor survey was to detect maser sources and locate their positions to better than the beam size. We assume that the sensitivity of the telescope beam is a function of the distance to beam centre, represented by a Gaussian distribution. We reconstruct the spectra at each position in the observed grid by combining each spectrum with the available adjacent spectra in the grid, weighted by their variance and the Gaussian weight corresponding to the distance between the grid points. With this process, we improve the signal-to-noise ratio and detection sensitivity. By integrating the flux of the strongest spectral feature in each spectrum, we construct the intensity map shown in Fig. 2. This map shows the location of the strongest intensity peaks; in a second step the spectra at each of those intensity peaks and closely surrounding ones are checked (e.g. for velocity consistency) to separate bona fide maser sources from spurious peaks. The detection sensitivity is ∼1 Jy km s⁻¹ (∼5σ). It can be seen from this image that there are two main flux enhancement regions: a complex region towards the top, that actually includes multiple masing sources, and a single source area towards the bottom of the diagram.

On kinematic and flux intensity grounds, we have identified four distinct water maser peaks in 30 Dor. In each spectrum where the maser emission is present, we measure the peak intensity of each component at the velocities listed in Table 2. We obtain a spatial representation of the intensity of each component that we fit with a two-dimensional Gaussian distribution with three free parameters: the amplitude and position (x, y) of the centre – the width of the distribution is fixed by the beam size. The amplitude translates into the intrinsic intensity of the source, and the centre is converted into right ascension and declination coordinates of each component, with a typical positional accuracy of a quarter of a beam size, ∼20 arcsec. In Table 2, we list the measured velocity, intensity and position of each maser source, as well as their identifications (see below). The last column provides the pointings at which the masers were detected (Fig. 1). The maser spectra are presented in Fig. 3.

0539−691 was first detected at 22 GHz by Whiteoak et al. (1983), in a region ∼1.5 arcmin northeast of R 136. van Loon & Zijlstra (2001a) further analysed this region, detecting 0539−691 as well as a new water maser source, 0539−691B, located ∼2.5 arcmin southeast of R 136. On kinematic grounds, the authors distinguish two masing sources in 0539−691, one with a velocity consistent with the systemic velocity of the local ISM (vLSR ∼270 km s⁻¹) – this is the source originally identified by Whiteoak et al. (1983) and also

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1 http://www.astro.rug.nl/IRAS-Server/
2 http://ssc.spitzer.caltech.edu/archanal/
Table 2. Observed properties of water maser detections: peak velocity, peak intensity, source position and pointings identification (for 30 Dor only; Fig. 1). We estimate that the positions in 30 Dor are accurate to about a quarter of a beam size, approximately 20 arcsec. 0539−691C is a hitherto unknown component. For the other sources, we are not able to compute accurate positions; for these, telescope-pointing positions are listed. No maser emission was detected towards N 157B and thus we provide the rms level in the spectrum.

| Maser source | Peak velocity (km s$^{-1}$) | Peak intensity (Jy) | RA 2000 (h m s) | Dec. 2000 (°’’’’) | Pointings identification |
|--------------|-----------------------------|---------------------|-----------------|------------------|------------------------|
| 0539−691a    | 269.5                       | 2.75 ± 0.60         | 05 38 49.9      | −69 04 34        | 6, 7, 10, 11, 12, 14, 15, 18, 19 |
| 0539−691b    | 261.0                       | 0.38 ± 0.09         | 05 38 55.2      | −69 04 12        | 6, 10, 11, 18, 19      |
| 0539−691B    | 194.0                       | 0.36 ± 0.09         | 05 39 04.3      | −69 07 52        | 32, 36                 |
| 0539−691C    | 266.0                       | 1.01 ± 0.27         | 05 38 47.1      | −69 06 06        | 19, 20, 25, 29, 30    |
| N 113a       | 253.0                       | 73.8 ± 16.0         | 05 13 23.1      | −69 22 34        |                        |
| N 113b       | 254.5                       | 19.4 ± 4.4          | −              | −                |                        |
| N 113c       | 251.0                       | 4.6 ± 1.1           | −              | −                |                        |
| N 113d       | 258.0                       | 2.0 ± 0.5           | −              | −                |                        |
| N 160A       | 253.0                       | 3.3 ± 0.7           | 05 39 42.7      | −69 38 26        |                        |
| N 105A       | 260.0                       | 1.5 ± 0.3           | 05 09 50.7      | −68 53 23        |                        |
| N 157B       | −                           | 0.13 (rms)          | 05 37 40.2      | −69 11 00        |                        |

*a* A more accurate position for this source can be found in Lazendic et al. (2002).

*b* This position is 1 arcmin to the west of the peak IR emission.

observed by Lazendic et al. (2002) – and a component blueshifted by ∼70 km s$^{-1}$. 0539−691B was also found to be blueshifted with respect to the systemic velocity by ∼90 km s$^{-1}$.

We find that the maser 0539−691 comprises two components (a and b) with peak velocities ∼261 and 270 km s$^{-1}$. They are very close (∼1.0 arcmin) and component b is rather weak, thus it is conceivable that it is a single source. Lazendic et al. (2002) also detect a component with peak velocity 269.5 km s$^{-1}$ and they pinpoint its location very accurately. They claim that their spectrum also contains additional faint emission extending down to 258 km s$^{-1}$ that might be related to our component b. We did not detect the blueshifted component detected in 0539−691 by van Loon & Zijlstra (2001a). We do identify a weak source with peak velocity of ∼194 km s$^{-1}$, located ∼4.6 arcmin from 0539−691, with 0539−691B (van Loon & Zijlstra 2001a). We have discovered a new maser source closer to R 136 (∼2.8 arcmin South from 0539−691), that we call 0539−691C. It has a velocity of ∼266 km s$^{-1}$, consistent with the systemic velocity. Despite the large survey area, this is the only new component we identified. No maser emission was detected towards N 157B, at a rms level of 0.13 Jy but note that the target was not well centred in the telescope beam.

3.1.2 Sparse map of N 113

Water maser emission at 22 GHz was first observed in N 113 by Whiteoak & Gardner (1986). We performed five pointings in this region. The method used to analyse the spectra of N 113 is similar to what was outlined in the previous section for 30 Dor, except with fewer pointings. In Fig. 4, we plot the central spectrum of our mosaic of pointings in N 113, with four components identified as a, b, c and d.

We were not able to disentangle the positions of the different components, so we cannot establish positively how many spatially distinct masers are there in this region. However, from the analysis of the peak intensity variations in our mosaic of pointings, we find evidence that component c might originate from a different position than the remaining components: at the position northwest of the central pointing, the peak intensity of component c was reduced by...
Figure 4. Water maser sources detected in N 113. This spectrum is the central one from our five-position sparse map (see Section 2.1). The different components are labelled a, b, c and d.

\[ \sim 60 \text{ per cent, while the peak intensities of the other components were reduced by } \sim 96 \text{ per cent.} \]

Lazendic et al. (2002) recently identified two distinct maser sources in N 113, 26-arcsec apart, and with peak velocities of 253 and 250 km s\(^{-1}\). We identify our multiple component source a, b and d with the Lazendic et al. (2002) component at 253 km s\(^{-1}\); based on the peak velocity, we believe our component c is the Lazendic et al. (2002) component at 250 km s\(^{-1}\). The strongest maser component is weaker than in the Lazendic et al. (2002) measurements. We note that water maser emission associated with YSOs is known to be variable both in intensity and in velocity (Palagi et al. 1993; Tofani et al. 1995).

3.1.3 Other regions in the LMC

Fig. 5 shows the maser detections towards N 160A (top) and N 105A (bottom). We are unable to derive accurate position information from these observations, but both these sources have also been observed by Lazendic et al. (2002), providing positions with subarcsecond accuracy. The maser spectrum of N 105A is similar to that reported previously, both in kinematic complexity and in intensity. For N 160A two maser locations, approximately 44 arcsec apart have been identified previously at essentially the same velocity. It is very likely that both those components contribute to the signal in our spectrum; indeed the flux ratios of the brighter component at 253 km s\(^{-1}\) to the other two components at 248 and 259 km s\(^{-1}\) are consistent with what would be expected if the two components of Lazendic et al. (2002) were combined.

3.2 VLT 3–4 \(\mu\)m observations

The \(L'\)-band acquisition images of N 157B and N 105A (Fig. 6) allow us to identify a number of red sources other than the two spectroscopic targets. Aperture photometry was performed on all sources in each image. Very red objects (typically \(K_s - L' > 1\) mag) are referred to as ‘IRS’, and these are numbered on the basis of the \(K_s - L'\) colour and \(L'\)-band brightness. These IRS objects have significant excess emission at 3 \(\mu\)m (Fig. 7) and are not simply reddened objects behind the molecular clouds. The other point sources are referred to as ‘S’, and these are numbered with increasing RA. Two other sources in N 105A seem to be diffuse in nature, at least in the \(L'\) band, so they are named blob A and B (see discussion below). The identification, 2MASS positions and magnitudes and \(L'\)-band magnitudes are listed in Table 3. In the next sections, these sources and the IR spectra are described in detail.

3.2.1 Infrared sources in N 157B

MSX LMC 888 (=IRAS 05381–6912; Egan et al. 2001) is a bright mid-IR point source in the 30 Dor region, situated within 1 arcmin from N 157B [usually identified as SNR 0538–69.1, although Chu et al. (2004) question the nature of the nebula as a supernova remnant]. Close to N 157B there is a small molecular cloud, JGB 30 Dor-22, with a diameter of 6.8 pc identified from CO observations (Johansson et al. 1998). The cold emission from the molecular cloud...
appears spatially resolved on MSX images, whilst the bright mid-IR source stands out through its warmer unresolved emission.

In our $L'$-band image (Fig. 6), the MSX source is easily identified as a bright IR star, that we call N 105B IRS1. There is at least one other star nearby also with extreme $K_s - L'$ colour, N 105B IRS2. IRS2 is seen in the direction of the molecular cloud and may be located behind it, but its very extreme $K_s - L'$ colour suggests it could also be a young object embedded in the cloud, warming the surrounding dust. IRS2 is considerably fainter than IRS1. N 105B IRS1 and IRS2 have ($J - K_s ) > 1.3$ mag but ($K_s - L'$)$< 0.5$ mag and are likely suffering from extinction by dust within the molecular cloud.

The spectrum of N 105B IRS1 (Fig. 8) seems at first glance featureless. It does not resemble spectra of evolved stars, for example, a heavily reddened, late-M type giant (cf. Matsuura et al. 2005; van Loon et al. 2006). There is also no evidence for H recombination emission lines arising from an ionized region (Section 3.2.2). When the spectrum is plotted as optical depth with respect to a continuum (a low-order polynomial fit), there seems to be a hint of the broad water ice feature at 3.1 $\mu$m, similar to that in IRAS 05328–6827 (van Loon et al. 2005b) also in the LMC. The evidence is, however, not conclusive with a column density at most $N$(H$_2$O)$< 10^{17}$ cm$^{-2}$. It is unclear what are the narrow absorption features bluewards of 3.5 $\mu$m.

### 3.2.2 Infrared sources in N 105A

MSX LMC 80 (=IRAS 05101–6855; Egan et al. 2001) is a bright IR source in the H$\alpha$ region LHA 120-N 105A. It is associated with an IR object that was suggested by Epchtein et al. (1984) to be a ‘protostar’. This object, which we will refer to as N 105A IRS1, is very bright in the $L'$ band (Fig. 6) and with $K_s - L' = 3.9$ mag it is extremely red (Table 3). It is not detected in the $J$ and $H$ band of 2MASS, so it is probably heavily extincted.

LHA 120-N 105A blob is associated with a small but extended nebulousity at a projected distance of 14 arcsec from IRS1 and 10 arcsec from S8, the WR star Br 16a (Dopita et al. 1994). We identify a bright core, blob A, surrounded by patchy emission visible in the $L'$-band image (Fig. 6). This diffuse core has a point-source 2MASS counterpart, but the 2MASS images seem to show some diffuse emission too. We have assigned an identifier to one of these patches, blob B, because it happened to fall in the slit of the spectrograph and produce a clear signal (see below). Continuum emission was detected at 6.6 GHz (Ellingsen et al. 1994), centred on IRS1 and blob A, connecting the two sources. It thus appears that both these sources are embedded in an ionized environment (see below), probably created by IRS1 itself or a source within blob A. The ($K_s - L'$) colour of the bright knot blob A is not particularly

| Name      | IRAC 3.6 $\mu$m | IRAC 4.5 $\mu$m | IRAC 5.8 $\mu$m | IRAC 8.0 $\mu$m | IRAC 8.28 $\mu$m | MSX 12.1 $\mu$m | MSX 14.7 $\mu$m | MSX 21.3 $\mu$m | MSX 12 $\mu$m | IRAS 25 $\mu$m | IRAS 60 $\mu$m | IRAS 100 $\mu$m |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|---------------|---------------|---------------|--------------|--------------|--------------|
| N 105B IRS1 | 0.173           | 0.313           | 0.483           | 0.635           | 0.96 ± 0.04     | 1.62 ± 0.09    | 1.89 ± 0.12    | 4.2 ± 0.3     | 4.0 ± 0.3    | 25 ± 3       | 170 ± 20     | 140 ± 40      |
| N 105A IRS1 | 0.028           | 0.063           | 0.181           | 0.473           | 1.72 ± 0.07     | 4.70 ± 0.24    | 6.61 ± 0.40    | 20.7 ± 1.2    | 8.0 ± 0.3    | 56 ± 2       | 310 ± 10     | 400 ± 20      |
red (Fig. 7) even though \((J - K_s) = 1.51\) mag suggests some extinction.

IRS2 is a very faint source located within \(\sim 0.5\) arcsec from the positions of the water (Lazendic et al. 2002) and OH masers (Brooks & Whiteoak 1997). It was not detected in the 2MASS survey, but appears as a very faint star in our \(L'\)-band image (Fig. 6). Given the low density of stars in the image, the association with the masers is suggestive. This object could be an embedded YSO. The methanol maser detected by Sinclair et al. (1992) unfortunately falls just outside the SE corner of the field of the \(L'\)-band image (see also Ellingsen et al. 1994).

Several more sources can be identified from Fig. 6. They all appear stellar in nature and have \((K_s - L') < 0.6\) mag. S6 and S9 have

\[ \text{Figure 6.} \quad \text{\textit{L'}-band acquisition images of N157B (top) and N105A (bottom), with identified stellar sources (‘S’) and infrared sources (‘IRS’). For N157B, the slit was centred on IRS1 and aligned N–S, while for N105A the slit orientation was chosen to include the diffuse source blob A (see text). The faintest stars in the images are } L' = 12.76 \text{ mag (N157B S3) and } L' = 14.30 \text{ mag (N105A IRS2), respectively.} \]

\[ \text{Figure 7.} \quad \text{Absolute } L'\text{-band magnitudes versus } K_s - L' \text{ colours for objects near N157B (open circles) and N105A (filled circles). Approximate empirical sequences from van Loon et al. (2005a) are overplotted for the red giant branch (RGB), red supergiants (RSG) and asymptotic giant branch (AGB; with mass-loss evolution); early-type main-sequence stars have } K_s - L' \sim 0. \text{ The effect of } A_V = 30 \text{mag extinction is also shown. Only three of the sources in this diagram are particularly red.} \]
Figure 8. Spectrum of the massive YSO candidate N 157B IRS1 in the 30Dor region. The strong 3.32-μm telluric methane feature has been removed. The spectrum shows no H recombination emission lines. The lower panel shows the optical depth with respect to the continuum (dotted line in the top panel); there might be a hint of the broad water ice feature at 3.1 μm.

along the slit (Fig. 10). A spatial profile for the continuum emission is obtained by averaging many columns on the array at either side of the emission line. After subtracting this continuum (solid lines in Fig. 10), the line profile has broad wings and shows a clear asymmetry with emission in the west-south-west (WSW) moving towards us, and emission in the east-north-east (ENE) moving away. This is strong evidence for a bipolar outflow originating near the centre of IRS1, at a projected velocity of \( v_{\text{bipolar}} \sim 100–200 \, \text{km} \, \text{s}^{-1} \) at a few tenths of an arcsecond (\( \sim 0.1 \, \text{pc} \)) at either side of the star.

Blobs A and B also show emission in the H recombination lines but in this case P66 is also detected (Fig. 9), indicating that extinction by dust is less severe than towards IRS1. Continuum emission in this source is extremely faint, if at all present. Both components show evidence for broad emission around 3.3 μm underlying the P66 line. The shape of this emission is consistent with the 3.28 μm unidentified IR feature that is usually attributed to Polycyclic Aromatic Hydrocarbons (PAHs; Allamandola, Tielens & Barker 1985). The Br\( \alpha \) to Pfy flux ratio for blob A is \( \sim 5 \), which might suggest that Br\( \alpha \) is optically thick (Drew et al. 1993).

The spectrum of blob A seems broader than IRS1 and exhibits a double-peaked line profile (Fig. 9), suggestive of an outflow also emanating from this nebular object. The position–velocity diagram of the Br\( \alpha \) line (Fig. 11) shows a kinematically broad emission suggesting a compact outflow at a projected velocity of \( v_{\text{outflow}} \sim \pm 300 \, \text{km} \, \text{s}^{-1} \). The spectrum shows departures from spherical symmetry: the brightest emission, at \( \sim 0.2 \, \text{arcsec} \) to the WSW of the core of blob A, is associated with gas that is preferentially moving towards us. Blob B, on the other hand, is kinematically cold and shows no signs of outflow. This seems to suggest that there might be a source powering an outflow in blob A, even if there is no evidence of free–free continuum from an ionized medium.

3.3 SEDs of N 157B IRS1 and N 105A IRS1

We performed aperture photometry in the IRAC images for the objects identified in the \( L' \)-band images, obtaining both fluxes and magnitudes (Reach et al. 2005). The 3.6-μm magnitudes agree quite well for most sources in N 105A and N 157B, except for the objects in areas where the ‘nebulosity’ appears denser (Figs 14 and 15).
IRAS data have poor spatial resolution and probably include emission from cold dust surrounding the YSO candidate. Fits obtained with the DUSTY code are overplotted as dotted curves (see text).

In these areas, the background is not correctly estimated, and measured fluxes are depressed. Nevertheless, the colours of these objects can still provide another hint on their nature. We briefly discuss here only the objects with measurements in the four IRAC bands: N 105A IRS1, IRS2, blob A+B and S2, and N 157B IRS1 and IRS2.

Jones et al. (2005, and references therein) defines the locus for red giants, Class II YSOs (objects with disks), Class I YSOs (embedded objects) and H II regions. N 105A S2 has colours consistent with it being a red giant. N 105A IRS2, N 157B IRS2 and N 105A blob A+B have colours consistent with H II regions, i.e. regions with ionized gas and less dust column density. N 105A IRS1 has colours consistent with a very reddened compact H II region, in agreement with the presence of H recombination lines in its spectrum, reddening determination and the findings of the SED analysis (see below). N 157B IRS1 has colours consistent with an embedded (Class I) YSO.

Table 4 lists the mid-IR photometry available for N 157B IRS1 and N 105A IRS1. The SEDs of N 105A IRS1 and N 157B IRS1 were reproduced with the dust radiative transfer model DUSTY (Ivezić Nenkova & Elitzur 1999), as an attempt to derive approximate quantitative information about these YSOs. The fits are shown along with the observed SEDs in Fig. 12, and the main fit parameters are summarized in Table 5. In both the cases, we could obtain a reasonable fit to the SED with a radial dust density profile $\rho(r) = \rho_0(r/r_0)^{-1.5}$ (steady accretion), and a standard MRN grain size distribution (Mathis, Rumpl & Nordsieck 1977). The dust envelope was assumed to be spherically symmetric; this is probably not strictly true. The bolometric luminosity is derived from scaling the model SED to fit the observed SED and using a value for the distance to the LMC of 50 kpc.

The main difference between the two objects is in the nature of the central source. In the case of N 157B IRS1, we place a blackbody of 25 000 K in the centre of the dust envelope. Such hot star is required to reproduce the SED throughout the JHK bands where the star becomes notable; at longer wavelengths (including the 3–4 $\mu$m band) the SED is dominated by dust emission. Based on the SED analysis alone, we cannot entirely rule out the possibility that this is an evolved dust-enshrouded red supergiant of around 10–15 M$_\odot$. However, this would imply a rather long (~20 Myr) time gap between the formation of this massive star and the star formation that is currently taking place in the 30 Dor region – Walborn & Blades (1997) identified five different stellar populations in the 30 Dor nebula, with ages in the range <1 and 10 Myr. A chance coincidence of such rare object with N 157B is extremely unlikely. Furthermore, the cautious identification of water ice (Section 3.2.1) argues against it.

In the case of N 105A IRS1, the 3–4 $\mu$m spectrum clearly indicates the presence of an ionized region inside of the dust envelope. We thus represented the central source by a free–free emission object. There can be little doubt that this is a young object and the surrounding dust is not produced by the central star, and we therefore used a mixture of amorphous oxygen-rich silicates (Ossenkopf, Henning & Mathis 1992) and carbon (Hanner 1988). The SED is.

![Figure 11](https://example.com) Position–velocity diagram of the N 105A blob A+B nebulousity, showing emission in the Br$\alpha$ line. The contour levels range from $1.1 \times 10^{-5}$ to $3.5 \times 10^{-5}$ W m$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$ in increments of $3.5 \times 10^{-6}$ W m$^{-2}$ $\mu$m$^{-1}$ sr$^{-1}$. Blob A resembles an expanding, asymmetric shell whereas blob B is a compact, kinematically cold cloud.

![Figure 12](https://example.com) SEDs of N 157B IRS1 (top) and N 105A IRS1 (bottom). The IRAS data have poor spatial resolution and probably include emission from cold dust surrounding the YSO candidate. Fits obtained with the DUSTY code are overplotted as dotted curves (see text).

| Name        | Central source | Dust type          | $T_{in}$ (K) | $\rho_{in}$ (g cm$^{-3}$) | $r_{in}$ (au) | $r_{out}$ (pc) | $A_V$ (mag) | $L$ (L$_\odot$) |
|-------------|----------------|--------------------|-------------|---------------------------|--------------|---------------|-------------|-----------------|
| N 105B IRS1 | 25 000 K blackbody | Silicate          | 730         | $8 \times 10^{-19}$      | 350          | 1.7           | 23          | $7.8 \times 10^4$ |
| N 105A IRS1 | Free–free (911 Å–10 cm) | 0.7 silicate + 0.3 carbon | 350         | $2 \times 10^{-19}$      | 2500         | 1.2           | 48          | $2.5 \times 10^5$ |

Table 5. Input parameters for, and results from the modelling with the DUSTY code of the SEDs of the embedded YSOs N 157B IRS1 and N 105A IRS1. Both make use of a standard MRN grain size distribution (see text).
Figure 13. Optical and IR images of N 113. The Hα emission (top left) and pseudo-continuum (top right) images cover approximately 4.4 × 6.7 arcmin² centred at ∼05h13m25s, −69 22′ 26″. The grey-scale is logarithmic between 10⁴ and 3 × 10⁵ Rayleigh for the Hα emission image and between 200 and 3000R for the continuum image. The most important gas structures and stars are identified and labelled. The 8 μm IRAC/Spitzer image is shown at the bottom left (4.7 × 4.7 arcmin², centred at ∼05h13m27s, −69°22′28″; the scale indicates 1 arcmin; the grey-scale is linear between −5 and 100 MJy sr⁻¹). Maser sources (circles; Brooks & Whiteoak 1997; Lazendic et al. 2002) and a molecular core (square; Wong et al. 2006) are identified. At the bottom right is a false colour image where Hα emission and stars appear in blue while red is molecular cloud material bright in the 8-μm image. No attempt was made to remove artefacts from the IR image, for instance the ghost impressions caused by the brightest stars. In all images, north is to the top and east to the left.

3.4 Hα map of N 113

The Hα images of N 113 (Fig. 13) show a wealth of detail. The line emission is so strong that it is still apparent in the pseudo-continuum image (though at a much fainter level). The main extended structures are three regions of Hα emission to the east, north and west of the centre of the HII region: N 113F, N 113C and N 113D, respectively. This is emphasized by an obscuring lane running across the HII region, on to which are projected (from east to west) N 113A, N 113B and N 113E: ‘a chain of three small intense knots of nebulosity which, together, make up NGC 1877’ (Henize 1956). There is a fourth such knot – which we name N 113G – in between N 113A and N 113F. Although fainter, it stands out well against the dark dust lane.

N 113C and the lower surface brightness nebula BSDL 945 (Bica et al. 1999) to the east of N 113F each contain a particularly striking example of a shell with a central star (indicated in Fig. 13 as ‘shell 1’ and ‘shell 2’). These shells are likely to be stellar wind-blown bubbles with a dynamical time-scale of only a few ∼10³ yr (for a wind speed of the order of 10⁶ km s⁻¹). The central star of shell 1 can be identified with a B0−0.5III star (Wilcots 1994), but the central star of the larger shell 2 remains anonymous.

Several OB stars in N 113 have been described in the literature. Near the edge of the Hα emission, the evolved B2[e] supergiant HD 269217 (=Hen S 89, R 82, IRAS 05136−6925, MSX LMC 216) has enjoyed considerable attention. It was first mentioned in Merrill & Burwell (1933) as a B star with strong Balmer line emission. Descended from a 30 M⊙ main sequence star, it has been associated with circumstellar dust and found to move at a heliocentric speed of vₘ ∼ 240 km s⁻¹ (Zickgraf et al. 1986).
Another, little-studied emission-line star HD 269219 (= Hen S 90) is found further north and away from the H II region. Closer to the core of the H II complex, HV 2377 is an M-type suspected supergiant. Both around and embedded within N113 are a number of O9–B0.5 stars – either on the main sequence or slightly evolved (Brun et al. 1975; Wilcots 1994).

4 DISCUSSION

4.1 Triggered star formation in the mini-starburst 30 Dor and N 157B

The central area of the 30 Dor nebula (N 157A) exhibits a complex star formation history. As already mentioned, Walborn & Blades (1997) disentangled five distinct stellar populations in the central area of 30 Dor. The population located mainly in the molecular filaments to the west and northeast of R 136 shows spectroscopic evidence of extreme youth (<1 Myr). These infant objects are spatially related with bright, compact IR sources within a complex nebular and dust morphology (Hunter et al. 1995): pillars of molecular gas and dust and dark globules (Walborn et al. 1999; Walborn, Maiz-Apellániz & Barbá 2002), which are being photoevaporated by the intense radiation from the massive compact cluster R 136 (Hunter et al. 1995). Together with the maser sources, this constitutes strong evidence that star formation is ongoing in the nebula.

Fig. 14 shows the 8.0 μm IRAC/Spitzer image of 30 Dor. At this wavelength, the extended emission is dominated by hot dust and PAH emission. This figure also shows the location of young, embedded IR sources (J − H and H − K ≥ 1.5 mag) identified in the literature (Rubio et al. 1998; Brandner et al. 2001; Maercker & Burton 2005) as well as the maser sources. The water masers in 30 Dor are located in similar structures as the IR sources, surrounding R 136, suggesting that current star formation (not just recent star formation) is also concentrated near the interfaces of the molecular cloud complex within the influence sphere of the previous generation of massive O- and B-type stars. The large velocity difference between maser source components (Section 3.1.1) implies location in distinct structures in the ISM. As proposed by van Loon & Zijlstra (2001a), the highly supersonic velocities of some of the sources and their location near the rim of large gas superbubbles (e.g. Wang & Helfand 1991) strongly suggest that the masers occur at the collision fronts of rapidly expanding bubbles of ionized gas with the surrounding dense neutral material. If the masers trace the velocities of protostars within these environments, then this constitutes evidence that star formation was triggered at different locations by the massive stars’ feedback.

Our maser observations survey the central part of the 30 Dor nebula, covering the immediate neighbourhood of R 136 and the densest regions of the nebula. Even though the survey area is much larger than previous observations, we only identified one new maser source. We can compare our survey results to the galactic water maser luminosity distribution from Valdettaro et al. (2001). Assuming a median distance to high-mass star-forming regions in nearby spiral arms of a few kpc, we would expect the bulk of the water masers in 30 Dor to have integrated fluxes of the order of 0.1–1 Jy km s⁻¹, with a steep decline at the higher end. This suggests that, although close, our survey is not yet deep enough to reveal the bulk of the water maser population in 30 Dor. None the less, as all detected water masers are located at or near compressed interface regions, our survey provides evidence that most of the on-going massive star formation occurs in the presence of feedback.

The situation is less clear for the molecular material in N 157B, still in the 30 Dor region but located ~7 arcmin (100 pc) from R 136. We identify N 157B IRS1 as a candidate protostar from the analysis of its SED and from the tentative detection of water ice. We have detected no maser emission towards N 157B IRS1. Despite the 0.9 arcmin mismatch in position, our experience with the 30 Dor mapping (see e.g. analysis of 0539-691C) indicates that we would have detected emission from this source if stronger than ~1 Jy. We cannot exclude the presence of weaker emission, however water masers are normally associated with the earlier (hot core) stage when such objects are very weak in the IR (de Buizer et al. 2005) – IRS1 is the brightest source in our sample at near- and mid-IR wave-lengths. N 157B has been identified with SNR 0538-69.1, although its nature as a supernova remnant has been questioned (Chu et al. 2004). The age of the alleged supernova remnant is only ~5000 yr (Wang & Gotthelf 1998) and it is therefore impossible to already have led to the formation of stars in the nearby molecular cloud. It is possible that the formation of N 157B IRS1 was triggered by feedback from the nearby OB association LH99, but we have no direct evidence for this.

4.2 Triggered star formation in N 113

N 113 is a smaller and perhaps simpler H II region than the 30 Dor mini-starburst complex. Fig. 13 (bottom right) shows in great detail the interplay between the ionized gas and the molecular material in N 113. This image combines the Hα image (blue) with the 8 μm...
a column density of \(4.3 \times 10^5\). A less evolved H II region?

winds from massive stars. A similar scenario seems also likely for 
therefore presents a clear example of star formation triggered by the 
feedback from the nearby OB stars.

density enhancements are located near the interface with the hot 
gas; thus it is likely that the gas has been compressed as a result of 

The average molecular hydrogen density in the molecular cloud 
associated with N 113 is estimated at \(n_{\text{cloud}} \sim 200\, \text{cm}^{-3}\) (Wong et al. 2006) which, for a cloud radius of \(R_{\text{cloud}} \sim 15\, \text{pc}\), corresponds to a column density of \(N_{\text{cloud}} \sim 9 \times 10^{21}\, \text{cm}^{-2}\). This just exceeds the threshold for a diffuse cloud to cool and collapse to form stars, \(N_{\text{critical}} \sim 10^{21}\, \text{cm}^{-2}\) (Bergin et al. 2004). However, Wong et al. (2006) argue that the cloud must be strongly clumped, which would imply that most (geometrically) of the cloud is much less dense – possibly \(N_{\text{cloud}} < N_{\text{critical}}\). The dense molecular clump that was detected within this cloud has a radius of \(R_{\text{clump}} \sim 1.6\, \text{pc}\) and a molecular hydrogen density of \(n_{\text{clump}} \sim 10^5\, \text{cm}^{-3}\) (Wong et al. 2006) ; this yields a column density of \(N_{\text{clump}} \sim 5 \times 10^{22}\, \text{cm}^{-2}\), which comfortably exceeds the threshold for star formation. The strongest density enhancements are located near the interface with the hot gas; thus it is likely that the gas has been compressed as a result of feedback from the nearby OB stars.

To summarize, the scenario that emerges in N 113 is that in the 
compressed dense lane of neutral gas and dust star formation is 
occuring, pinpointed by the maser sources in its earliest stages and 
by the 1.3-cm continuum emission as the massive stars evolve. N 113 
therefore presents a clear example of star formation triggered by the 

4.3 N 105A, a less evolved H II region?

The situation seems different for N 105A. Fig. 15 (top) shows the 
8 \(\mu\)m IRAC/Spitzer image of N 105A, dominated by hot dust and 
PAH emission, with the positions of N 105A IRS1 (Epchtein et al. 1984; this work), water and OH maser (Brooks & Whiteoak 1997; Lazendic et al. 2002) and methanol maser (Sinclair et al. 1992) indicated. Although projection effects may affect our view, the morphology of N 105A shows little evidence for massive star feedback; no shell structure is seen in [O iii] images (Ambrocio-Cruz et al. 1998), in spite of the proximity of the OB association LH31, identified near the molecular cloud (Dopita et al. 1994). Furthermore, there seems to be no link between the water and OH maser source (Brooks & Whiteoak 1997; Lazendic et al. 2002) and the protostar location

and any external trigger. However, the methanol maser to the south 
(Sinclair et al. 1992) does appear to lie in a dense knot at the rim of 
a cavity in the molecular cloud. A massive YSO, N 105A IRS1, is 
already ionizing the molecular cloud and also shows evidence of 
outflows. It seems likely that it is only a matter of time before 
N 105A IRS1 starts sculpting the N 105 complex, influencing current 
star formation occurring in the cloud core as signposted by the 
maser sources.

The molecular cloud associated with N 105A is a factor of 5 
denser than that in N 113 (Chin et al. 1997). N 105A is therefore 
more likely to collapse and fragment without the need for an ex-
ternal trigger. Thus, N 105A seems to be at an earlier stage of its 
evolution, whereas N 113, N 160A and in particular 30 Dor have
seen more generations of stars forming prior to the current epoch of star formation.

5 SUMMARY AND CONCLUSIONS

We have conducted a survey for water maser emission in 30 Dor and a sample of H ii regions in the Large Magellanic Cloud to investigate the conditions under which current star formation occurs. The locations of the maser sources are compared with infrared images from the ESO/VLT (at 3.8 μm) and the Spitzer Space Telescope, and an Hα image in the case of N 113. We also present 3–4 μm spectroscopy to investigate the nature of two protostar candidates, in the N 157B and N 105A regions, showing evidence for the onset of the stellar feedback process in one of them.

Our water maser survey of 30 Dor uncovered one new source, 0539–691C, with a velocity consistent with the systemic velocity of the LMC. All detected water masers are located in the densest part of the nebula at the interface between neutral and ionized gas. N 105A IRS1 shows strong H recombination line emission, and its SED and IR colours are consistent with an embedded young massive star ionizing its immediate surroundings. It also shows evidence for outflows. A nearby diffuse IR source, N 105A blob, shows both H recombination and PAH emission. We identify N 157B IRS1 as an embedded protostar based on the analysis of its SED and a tentative detection of the 3.1 μm water ice feature.

In the well-developed H ii regions 30 Dor, N 113 and N 160A, no water masers have been detected deep within the molecular cloud complexes. They are always found at the interfaces between molecular cloud and H ii region. This provides strong evidence that feedback from massive stars triggers subsequent star formation. Although in the dense cloud N 105A star formation seems to occur without evidence of massive star feedback, the general conditions in the LMC seem favourable for sequential star formation as a result of feedback.

The wind speed and mass-loss rate of O and B stars decrease at lower metallicity (Mokiem & de Koter, in preparation), thus massive star feedback could be weak in metal-poor environments but we see no evidence for this in the LMC (metallicity ~40 per cent solar). This is important as the duration and intensity of star formation epochs in galaxies may depend on the efficiency of the local massive star feedback to trigger further star formation.

ACKNOWLEDGMENTS

We would like to thank the staff at Parkes, AAT and ESO Paranal for their support. We thank the anonymous referee for useful comments. This publication makes use of data products from 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration (NASA) and the National Science Foundation. We make use of archival images obtained with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. JMO acknowledges financial support by PPARC.

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APPENDIX A: REGIONS WITH NON-DETECTIONS AT 22 GHz

We have observed several other H II regions at 22 GHz, both in the LMCs and in the SMCs. The positions listed in Table A1 had been previously observed by Whiteoak et al. (1983) and Scalise & Braz (1982). We did not detect maser emission at any of these positions, confirming previous non-detections (Whiteoak et al. 1983).

Table A1. List of non-detections in the LMC and SMC.

| Cloud complex | RA 2000 (h m s) | Dec. 2000 (° ′ ″) | rms/Channel (Jy) |
|---------------|----------------|------------------|-----------------|
| Large Magellanic Cloud |               |                  |                 |
| MC 69         | 05 36 20.7     | −69 12 15        | 0.10            |
| MC 89         | 05 47 09.6     | −69 42 15        | 0.10            |
| N 11B         | 04 56 51.5     | −66 24 25        | 0.13            |
| N 132D        | 05 25 01.6     | −69 38 16        | 0.13            |
| N 158C        | 05 39 09.3     | −69 30 14        | 0.09            |
| N 159         | 05 39 57.2     | −69 44 33        | 0.10            |
| N 44D         | 05 23 01.0     | −68 02 13        | 0.10            |
| N 59A         | 05 35 24.5     | −67 34 52        | 0.13            |
| Small Magellanic Cloud |             |                  |                 |
| N 66          | 00 59 16.9     | −72 09 50        | 0.11            |
| S 7           | 00 46 38.9     | −72 40 50        | 0.10            |
| S 9           | 00 47 30.8     | −73 08 20        | 0.10            |

Figure B1. Time-series of the 22 GHz observations of R Dor. The top panel shows each individual spectrum subtracted by the average spectrum. The y-axis represents the actual time gaps between spectra. The average and variance spectra are shown in the panel below. Variability on the maser profiles seems to be restricted to the high-frequency component
Figure B2. Average 22 GHz spectra of R Dor, from this work (full line) and van Loon et al. (2001b, dot–dashed line). In 1.33 pulsation cycles (see text), the maximum peak intensity has shifted from the low- to the high-frequency component.

shows variability. R Dor pulsates radially in a semi-regular fashion with a period of \(P \sim 338\) d, but the variability of the water maser emission occurs on a much shorter time-scale – 9 d correspond to less than 0.03 cycles.

The average spectrum is compared in Fig. B2 to that observed 1.33 cycles previously (2000 April; van Loon et al. 2001b). The 2001 spectrum looks more similar to the discovery spectrum (Lépine, Paes de Barros & Gammon 1976), and is more symmetrical around the systemic velocity of the star as derived from the centroid of the CO emission profile, \(v_\star = 24\) km s\(^{-1}\) (Olofsson et al. 2002). The double-peaked water maser profile suggests substantial radial amplification; this yields an estimate for the outflow velocity in the inner part of the dust envelope of \(v_{\text{H}_2\text{O}} \sim 2\) km s\(^{-1}\) (peaks) to 4 km s\(^{-1}\) (total extent), which is less than the outflow velocity in the outer part of the dust envelope as measured in CO, \(v_{\text{CO}} \sim 6\) km s\(^{-1}\). This implies that the wind is still accelerating in the region of the water maser.

The water maser emission profile of W Hya (Fig. B3) has a single peak near the systemic velocity of the star, \(v_\star = 39.7\) km s\(^{-1}\) (González-Alfonso et al. 1998), suggesting mainly tangential amplification. However, the emission profile has a broader pedestal component suggesting radial motions of the order of \(v_{\text{H}_2\text{O}} \sim 2\) km s\(^{-1}\).

The water maser is highly variable, but the maximum extent of the emission is well constrained and suggests \(v_{\text{H}_2\text{O}} < 4\) km s\(^{-1}\) (Rudnitskii, Lekht & Berulis 1999). As in the case of R Dor, this is slower than the outflow velocity in the outer part of the wind as measured in CO, \(v_{\text{CO}} \sim 6.5\) km s\(^{-1}\) (Olofsson et al. 2002), and consistent with a wind that is accelerated through radiation pressure on dust grains.

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