

Supersonic water masers in 30 Doradus

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ABSTRACT

We report on extremely high velocity molecular gas, up to -80 km s^{-1} relative to the ambient medium, in the giant star-formation complex 30 Doradus in the Large Magellanic Cloud (LMC), as observed in new 22 GHz $\text{H}_2\text{O } 6_{16} \rightarrow 5_{23}$ maser emission spectra obtained with the Mopra radio telescope. The masers may trace the velocities of protostars, and the observed morphology and kinematics indicate that current star formation occurs near the interfaces of colliding stellar-wind blown bubbles. The large space velocities of the protostars and associated gas could result in efficient mixing of the LMC. A similar mechanism in the Milky Way could seed the galactic halo with relatively young stars and gas.

Subject headings: Masers – Stars: formation – ISM: bubbles – ISM: individual objects: 30 Dor – ISM: kinematics and dynamics – Magellanic Clouds.

1. Introduction

The most luminous H II region in the Local Group of galaxies is 30 Doradus (Tarantula nebula, N157: Kennicutt 1984; Walborn 1991) in the Large Magellanic Cloud (LMC). It is the site of recent star formation on a massive scale and harbours a rich stellar cluster (NGC2070) of which the core (R136: Feast et al. 1960) has only recently been resolved into many individual stars (cf. Hunter 1999). The H II region is embedded in an extended halo of expanding gas. In between, the stellar winds from the rapidly evolving massive stars interact with each other and with the surrounding interstellar medium (ISM) to create an intricate complexity of shells, filaments and dense knots (Meaburn 1980, 1984; Wang & Helfand 1991; Chu & Kennicutt 1994). The radiation from these hot stars photo-evaporates the surrounding dusty, molecular and neutral clouds (Hunter et al. 1995; Poglitsch et al. 1995; Scowen et al. 1998). It thus appears that the newly born stars destroy their parent Giant Molecular Cloud (GMC), which might prevent further star formation. Yet the recent discovery of protostars and structures similar to Herbig-Haro objects (Jones et al. 1986; Walborn

& Blades 1987, 1997; Hyland et al. 1992; Rubio et al. 1992, 1998; Walborn et al. 1999) provides ample evidence for the occurrence of current star formation, in spite of — or perhaps due to (Dopita 1981; Caulet et al. 1982; Dopita et al. 1985) — the violent interaction between colliding stellar-wind blown bubbles.

The first evidence of ongoing star formation in 30 Doradus was the detection of H₂O maser emission from 0539–691 (Whiteoak et al. 1983), a region $\sim 1.5'$ NE of R136. H₂O masers have been found in three more regions in the LMC (Scalise & Braz 1982; Whiteoak et al. 1983; Whiteoak & Gardner 1986) amongst which is 0540–696 in the GMC extending ~ 3 kpc due S of 30 Doradus (Israel 1984; Cohen et al. 1988; Kutner et al. 1997; Johansson et al. 1998). H₂O masers occur in dust-enshrouded (Class 0: Shu et al. 1987) Young Stellar Objects (YSOs) and Ultra Compact H II regions (e.g. Knapp & Morris 1976; Genzel & Downes 1977; Cesarsky et al. 1978; Rodriguez et al. 1978; Codella et al. 1994, 1996), and disappear once the H II region becomes diffusive after $\sim 10^5$ yr (Genzel & Downes 1979; Codella & Felli 1995). H₂O maser emission arises both in low-mass and massive YSOs (Haschick et al. 1983; Wouterloot & Walmsley 1986; Tereby et al. 1992; Wilking et al. 1994; Codella et al. 1995) but is more intense in massive cores of star formation (Palla et al. 1991; Henning et al. 1992; Palagi et al. 1993; MacLeod et al. 1998). Models (Elitzur et al. 1989, 1992) suggest that the H₂O masers occur in shocked layers at the neutral side of photo-dissociation regions (PDRs) around newly formed stars. Masers are extremely bright emission lines, that can be used both to probe the kinematics within the circumstellar environment as well as to trace the systemic velocity of the masing object.

Here we present new 22 GHz data of the known H₂O maser source 0539–691 and a hitherto unknown H₂O maser at $\sim 2.5'$ SE of R136. Both show discrete emission components at large blue-shifted velocities with respect to the bulk of the ISM in the 30 Doradus region. This places the masers and hence the star formation sites at the rim of expanding stellar-wind blown bubbles, providing new evidence for sequential, shock-induced star-formation.

2. Observations

The 22 m radio telescope at Mopra, Australia, was used from January 18 to 29, 1999, with the 1.3 cm receiver plus autocorrelator backend to observe the $6_{16} \rightarrow 5_{23}$ rotational transition of ortho-H₂O at a rest frequency of 22.23507985 GHz. The aim was to detect maser emission from circumstellar envelopes around evolved giants in the Magellanic Clouds (van Loon et al. 2000). While observing IRAS05280–6910, however, one of the background reference beams, pointed at $(\alpha, \delta)_{J2000} = (5^h 39^m 03.9^s, -69^\circ 08' 18'')$, picked up a signal from the 30 Doradus complex. This source will be referred to as 0539–691B. It is located only $\sim 3.3'$ away from the known H₂O maser 0539–691 (Whiteoak et al. 1983; Whiteoak & Gardner 1986) at $(\alpha, \delta)_{J2000} = (5^h 38^m 49.6^s, -69^\circ 04' 41'')$ that we observed as well. The beam FWHM was $2.7'$, corresponding to ~ 39 pc at the distance of the LMC (50 kpc).

The 64 MHz band width and 1024 channels centred at ~ 22.215 GHz yielded a velocity coverage of ~ 860 km s $^{-1}$ at 0.84 km s $^{-1}$ channel $^{-1}$. The system temperature $T_{\text{sys}} \sim 115$ K (50 to 65 K from the sky), and the opacity correction was between ~ 1.3 and 1.6. The conversion factor from antenna temperature to flux density was 20 Jy K $^{-1}$, consistent with the observed noise and flux density for R Dor (48 Jy). The on-source integration time on 0539–691B was 56 minutes. The baselines were constructed by heavily smoothing the spectra — excluding the maser peaks — with a gaussian of $\sigma = 50$ km s $^{-1}$, and these were then subtracted.

3. Results

3.1. Kinematics

The 22 GHz emission spectrum of 0539–691B peaks sharply at $v_{\text{hel}} = 201$ km s $^{-1}$ (Fig. 1, top panel). In 0539–691 the main component peaks at $v_{\text{hel}} \sim 266$ km s $^{-1}$ (Fig. 1, bottom panel) and may be double as was also observed in the early 1980’s (Whiteoak & Gardner 1986). The secondary peak in 0539–691, at a remarkably low $v_{\text{hel}} \sim 182$ km s $^{-1}$, was not known before. The source of this maser emission may be near the edge of the Mopra beam and hence outside the smaller Parkes beam. Other spikes in the spectrum of 0539–691 may be spurious. Both 0539–691 and 0539–691B peak at ~ 0.5 Jy, which is a few times fainter than 0539–691 in the early 1980’s. This might be due to temporal variability (see, for instance, Knapp & Morris 1976; Hunter et al. 1994; Persi et al. 1994).

The main emission component of 0539–691 around $v_{\text{hel}} \sim 266$ km s $^{-1}$ has a 21 cm H I counterpart (McGee & Milton 1966; Kim et al. 1999), which is seen in deep absorption. OH 1665 & 1667 MHz absorption is centred at $v_{\text{hel}} \sim 262$ km s $^{-1}$ (Gardner & Whiteoak 1985) and probably associated with the same region. The bulk of the nebular emission (Clayton 1987; Chu & Kennicutt 1994; Hunter 1994), Ca II interstellar absorption (Wayte 1990), $^{12}\text{CO}(1 \rightarrow 0)$ emission (Israel et al. 1986; Johansson et al. 1998) and radio recombination lines (Peck et al. 1997), as well as the velocities of supergiants (Wayte 1990) are within ~ 20 km s $^{-1}$ of a mean $v_{\text{hel}} \sim 270$ km s $^{-1}$. This indicates a systemic velocity of the 30 Doradus complex.

Strong H $_2$ O maser emission peaks within ~ 20 km s $^{-1}$ from the systemic velocity of the parent molecular cloud (Genzel et al. 1981; Tereby et al. 1992), because the amplification is tangential whilst the velocity field is mostly radial with respect to the source of photons (Elitzur 1992). In some cases masers with relative velocities > 100 km s $^{-1}$ are detected — possibly related to fast molecular outflows from the YSOs — but these masers are nearly always (much) fainter than the emission near the systemic velocity (Morris 1976; Genzel & Downes 1977; Rodriguez et al. 1978; Blitz & Lada 1979; Downes et al. 1979; Genzel et al. 1979). It is therefore unlikely that two out of three bright H $_2$ O masers in 30 Doradus would originate in such jets. Hence the large differences in velocity with respect to the systemic velocity of the 30 Doradus complex suggest that the H $_2$ O masers at $v_{\text{hel}} = 182$ and 201 km s $^{-1}$ are not associated with the bulk of the molecular gas in the 30

Doradus complex, but rather with compact knots or slabs in the ISM as they are also seen in the nebular (Scowen et al. 1998) and IR emission (Walborn et al. 1999); these structures often move supersonically with respect to the ambient ISM (e.g. Chu & Kennicutt 1994). The high-velocity H₂O masers may thus trace star formation in supersonic gas.

3.2. Morphology

The locations of the masers with respect to the IR emission in the 30 Dor region are shown in Fig. 2 (MSX 8.3 μm image from <http://www.ipac.caltech.edu/ipac/msx/msx.html>; Price & Witteborn 1995). The brightest IR emission is distributed in an arc-like geometry around the R136 cluster core. In the brightest part of this arc, to the NE of R136, is where the 0539–691 maser source is situated. It is also a region of intense H α , [C II] 158 μm , ¹²CO(1 \rightarrow 0) and far-IR continuum emission (Poglitsch et al. 1995) as well as strong thermal radio continuum emission (Peck et al. 1997). The Mopra beam at 22 GHz covers many individual IR sources of which some are multiple systems (Walborn et al. 1999), and in fact there has not yet been identified a definitive counterpart for the H₂O maser in this region. The newly discovered maser source 0539–691B is located to the SE of R136, seemingly centred on a moderately bright blot of IR emission that has received little attention in the literature and in which no candidate protostars have been proposed.

The H₂O masers and associated IR emission seem to be located in between some of the large expanding shells in the region (Numbers 1 through 5 in Fig. 2: Cox & Deharveng 1983; Wang & Helfand 1991). Some caution should be taken as to whether these shells are truly expanding or mere superpositions of non-uniform sheets and filaments (Clayton 1987; Scowen et al. 1998). The masers may be situated near the rim of stellar-wind blown bubbles filled with hot gas. X-rays trace this hot gas (Wang 1999) and show that bubbles #3 and #5 may already be bursting out of the molecular cloud environment, whilst hot gas may still be contained within a closed shell #1.

4. Discussion

The 22 GHz detections of 0539–691 & 0539–691B show clear morphological and, for the first time, kinematical evidence for the location of H₂O masers where rapidly expanding volumes of ionized gas collide either with other such gas volumes or with a neutral and/or molecular medium. The stellar-wind blown bubbles have supersonically swept up material from the surrounding ISM, which then became highly compressed and shocked. Upon the collision of such bubble with another bubble or with a dense cloud, this dense fast-moving layer becomes even more shocked and compressed. This may be a favourable condition for the formation of new stars (Dopita 1981; Caulet et al. 1982).

On kinematic grounds we can at least distinguish three masers: two in 0539–691 and one in 0539–691B. The large velocity difference between the 182 km s⁻¹ maser and the other maser

emission in 0539–691 strongly suggests also a large spatial separation and the location in distinct structures in the ISM. The exact location of the H₂O masers inside of the dense molecular layer may be either near the PDR around the protostar and/or near the PDR associated with the expanding shell. Until interferometric observations at 22 GHz are undertaken it is not yet possible to identify the masers with a particular structure as seen at other wavelengths. The reason is that the morphological and kinematical structure of the ISM within ~ 100 pc from R136 is extremely complex on all scales.

Protostar candidates in the 30 Doradus complex have been associated with dark globules that are being photo-evaporated externally (Clayton 1987; Rubio et al. 1992; Scowen et al. 1998; Walborn et al. 1999) and are situated in between expanding gas shells (Hyland et al. 1992). These shells range in size from ~ 0.5 pc around individual massive stars (Hunter et al. 1995), up to the ~ 50 pc size shells around associations of $\sim 10^2$ OB and/or Wolf-Rayet stars (Chu & Kennicutt 1994). In fact, both the size distribution of structures seen in H I (Stanimirović et al. 1999) and the size-turbulence relation of H II regions (Roy et al. 1986) obey a Kolmogorov scaling law. The co-existence of ionized and molecular gas in the PDRs at the interface of the shells and molecular clouds indicates highly localized (clumpy) and stratified physical structures (Poglitsch et al. 1995; Scowen et al. 1998). Poglitsch et al. estimate typical clump sizes of a few pc, containing a mass of $M \sim 10^{2-3} M_{\odot}$. This is just below the detection limit of the currently available CO surveys. Assuming a star formation efficiency of $\sim 10\%$ and a Salpeter-law Initial Mass Function (Salpeter 1955), the most massive star formed in a $10^3 M_{\odot}$ cloud is expected to have $M \sim 8$ to $10 M_{\odot}$ — i.e. an early-B type star with a luminosity of $L \sim 10^4 L_{\odot}$. Hence one or a few bright H₂O masers may be expected in such a star forming cloud.

It seems thus the case that star formation as traced by H₂O maser emission occurs at several locations in the 30 Doradus complex, which are associated with fast-moving gas ramming into other material. This confirms the picture of the propagation of sequential star formation, in which stellar-wind blown bubbles are now starting off a new epoch of star formation in 30 Doradus. It remains to be proven whether, in a similar fashion, the formation of the young stellar population of $\sim 10^6$ yr — that includes R136 and that is responsible for the H II region of 30 Doradus as we see it today — was induced by a previous star formation event $\sim 2 \times 10^7$ yr ago as traced by red supergiants within 45 pc from R136 (Hyland et al. 1992).

The star formation propagating throughout the 30 Doradus complex may initially have been triggered by ram pressure resulting from the supersonic motion of the LMC through the extended galactic halo (de Boer et al. 1998): the LMC appears to have been moving from apo-galacton at ~ 100 to 200 kpc one Gyr ago to peri-galacton at ~ 50 kpc today (Gardiner et al. 1994; Heller & Rohlfs 1994). A close encounter between the Magellanic Clouds ~ 2 to 5×10^8 yr ago (Gardiner et al. 1994; Heller & Rohlfs 1994) may also have played a rôle in stirring up the ISM in the LMC, triggering enhanced star formation as evidenced by common peaks in the age distributions of clusters in both Magellanic Clouds (Pietrzyński & Udalski 2000). More may be learnt about the triggering of sequential star formation from studies of the 3 kpc long reservoir of CO gas due S of

30 Doradus (Israel 1984; Cohen et al. 1988; Kutner et al. 1997) that seems to be in an earlier stage of star formation activity than the 30 Doradus complex (Heydari-Malayeri et al. 1999).

If the newborn stars have space velocities similar to those of the H₂O masers, then these stars will quickly mix with the older stellar populations of the LMC. Together with the ejection of stars by supernovae in binaries (Zwicky 1957; Blaauw 1961; Kaper et al. 1997; Hoogewerf et al. 2000) and dynamical interactions within young clusters (Poveda et al. 1967; Gies & Bolton 1986; Hoogewerf et al. 2000), high-velocity star formation may thus provide an additional mechanism for the formation of runaway stars. In fact, it has been argued that the star cluster associated with SN 1987A has formed at a velocity of 50 km s⁻¹ relative to the disk (Graff & Gould 2000). Such high velocity corresponds to 5 kpc in 10⁸ yr, sufficient to cross the bar of the LMC. Thus both gas and young stars may efficiently mix throughout the entire galaxy.

There is some indication that this may also happen in the Milky Way: the presence of early-type Main-Sequence stars in the galactic halo (Rolleston et al. 1999) may be explained by their formation in gas entities that were being ejected out of the galactic disk. Some of this gas may fall back towards the galactic disk in the form of high-velocity clouds (Richter et al. 1999). We see the galactic disk edge-on, but the LMC disk nearly face-on, which makes it much easier to detect this escaping gas and associated star formation in the LMC than in our own Milky Way galaxy.

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Fig. 1.— H_2O maser emission (22 GHz, Mopra) from 0539–691B (top panel) and 0539–691 (bottom panel). The velocities are heliocentric. The boldfaced curves are the spectra smoothed by a gaussian of $\sigma = 2 \text{ km s}^{-1}$.

Fig. 2.— MSX $8.3 \mu\text{m}$ image of the 30 Doradus region, with the beams pointed at the H_2O maser sources 0539–691 and 0539–691B, as well as the location of the OB association R136, the supernova remnant N157B, and five shells as designated by Cox & Deharveng (1983) and Wang & Helfand (1991).

