Part I. Star Formation

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Star formation: Relationship between the maser species

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Abstract.

Masers in Star Formation Regions arise chiefly from the molecules of methanol, hydroxyl, and water; in the case of methanol and hydroxyl, masing transitions are numerous. Exploring the relationship between the maser species (and their relationship to any associated ultracompact HII region detectable at radio wavelengths) can be made at two levels: first, at the general level, assessing whether the occurrence together of some species, and the absence of others, reveals significant properties of the site as a whole; second, at a deeper level, to assess whether the masing spots are coincident in both velocity and space.

The first may be used as a diagnostic of the evolutionary state of the embedded young massive star. The second reveals physical conditions.

New studies relevant to these issues are discussed here. Substantial unbiased surveys of the major masing transitions are especially valuable in allowing a more effective interpretation of existing targeted observations.

1. Introduction

The previous meeting devoted to astrophysical masers in 1992 (Clegg & Nedoluha 1992) was held very shortly after the first detection of the strongly masing 6.6-GHz transition of methanol (Menten 1991). A flurry of first results on this topic revealed their immense potential for improving our understanding of masers in massive star forming regions (SFRs). Nearly ten years later we will see in this review that methanol has fulfilled its promise, especially for studies of relationships between methanol masers of various transitions, and with masers of OH.

We may contrast that with the early years of water maser searches towards OH masers. Success rates were low and, disconcertingly, the archetypal OH maser W3(OH) had no water maser; an apparent water counterpart proved to be a clearly separate source (Forster, Welch & Wright 1977). So it was not obvious that there would be many sites where different species would be intermingled.

In this review I will deal principally with transitions of methanol (but only the class II masers) and OH, together with the 22-GHz transition of water, and the radio continuum that can often reveal a related ultracompact HII (UCHII) region: the mainstream varieties of masers in SFRs. Elsewhere in this meeting there is coverage of the rarer transitions such as the SiO masers of which three are known in SFRs, the formaldehyde masers likewise, the ammonia masers, and the class I methanol masers, and they will not be further discussed here.

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The classification of masers needs a few words to dispel any confusion. A major division is between masers associated with massive young stars, and masers around less massive, old (late-type), stars. The former, SFR masers, occurring in regions of massive star formation, are commonly referred to as 'interstellar' on the assumption that the masing material originates from the interstellar medium immediately surrounding the (stellar) source of excitation. Masers around late-type stars are termed 'circumstellar' since the masing material originates from the outer envelope of the central exciting (evolved) star. But there is little difference in appearance to distinguish these varieties. The term 'OH/IR objects' is commonly used for circumstellar masers where the late-type star is manifested only indirectly, by the IR emission from its obscuring dust shell; yet arguably it equally describes masers in star formation regions, where a dusty envelope obscures the early-type star and reprocesses its optical emission to the IR.

'SFR masers' encompass those that seem to have a massive young star as a central object, those associated with a hot core (perhaps an earlier SF phase), and those associated with less massive, but young, stars, often currently defined as YSOs, and with maser emission chiefly confined to water.

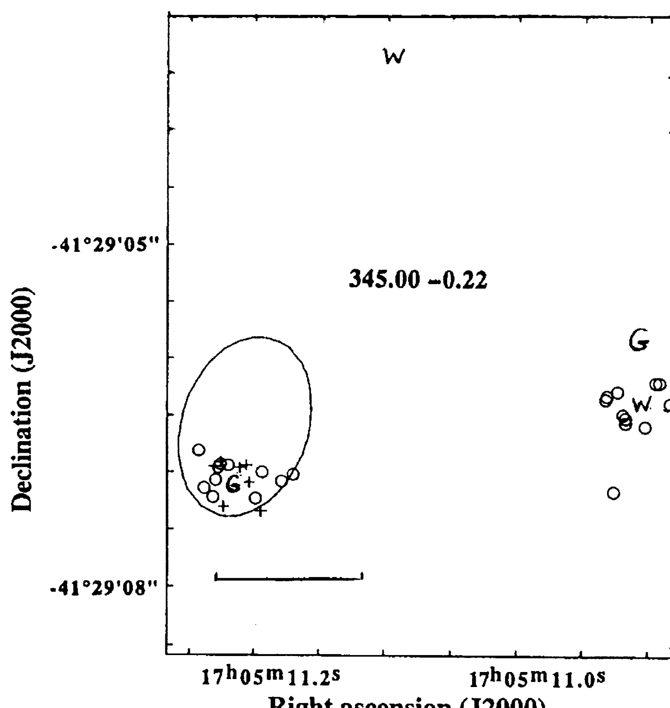

Figure 1. Masers in a region of massive star formation, 345.00-0.22. At a distance of 3.2 kpc, the bar depicts 20 mpc. Symbols denoting maser spots of each species are: 6668-MHz methanol (o), OH (+ for excited OH at 6035 MHz and G for ground state OH at 1665 MHz) and water (w); a UCHII region has its boundary shown as an ellipse.

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2. Relationships at several levels

To illustrate my nomenclature, and the kinds of relationships to be considered, we look at a typical region of star formation shown in Fig. 1, with its rich mixture of maser spots of methanol, OH and water, together with a UCHII region.

Maser spots are the smallest entities, with typical size of a few milliarcsec, and velocity widths less than 1 $\mathrm{km\,s^{-1}}$. Fig. 1 displays three maser sites (close groupings of maser spots). Each site has typical extent of less than 30 mpc (1 arcsec at 6 kpc) = 6000 AU or 10^{15}m. This equates to 33 light days, useful to bear in mind when looking at time scales of variability.

The evidence of Section 4 suggests that the source of excitation of each site is an embedded very young or embryonic star; this is clearly the case for the masers that coincide with the UCHII region (where we have methanol, ground-state OH, and 6035-MHz excited OH). A second site at smaller RA has strong methanol maser emission, water masers, and weak 1665-MHz emission; and a third site (to the north) displays only water maser emission.

The data displayed in Fig. 1 come from several independent investigations: the basic 6668-MHz methanol, 6035-MHz OH, and UCHII data were taken from Caswell (1997); the water masers from Forster & Caswell (1989, 1999), with positions correctly registered using the UCHII region; and the ground state 1665-MHz OH from both Forster & Caswell and Argon, Reid & Menten (2000), where intermingling of ground-state and excited-state OH is used for registration.

Thus relationships to be explored occur at the most general level (to reveal a cluster of three sites); at a more detailed level (to explore what maser varieties may be intermingled within a site); and at the most precise level (where we can ask whether there is coincidence of different types of maser spots).

3. Surveys

In order to explore the relationships of maser sites associated with young (or embryonic) massive stars, ideally, we would begin with surveys for the accepted signposts of massive star formation that are complete over the whole Galactic plane (in our dreams, the whole sky). Although our inventory of the fully fledged O and B stars may be quite good, our recognition of sites at earlier stages, when the star is optically obscured by its initial dust cocoon, is woefully incomplete. These earlier stages can be identified by the presence of UCHII regions detected in the radio wavelength regime, by IR emission from the dusty cocoons themselves, and by radio line thermal emission from molecular cores with central temperatures exceeding 100 K (commonly referred to as 'hot' cores).

With regard to the masers, we desire similarly complete, deep, surveys for all molecular maser species (assuming that the currently known ones of OH, methanol, water, and a few other less common ones, constitute the major maser varieties that exist in Star Formation Region maser sites).

What unbiased maser surveys do we have?

OH has been searched for extensively in the four 1.6-GHz transitions of the ground state with the Parkes telescope (Caswell & Haynes 1987 and references therein), following pioneering pilot studies from Onsala. Supplementary surveys with the AT compact array have recently added to these (Caswell 1998).

For 22-GHz water masers, a survey by Matthews et al. (1985) has begun this heroic venture, but represents only the 'tip of the iceberg' (so to speak): two narrow Galactic plane strips in longitude ranges 19°-23° and 29°-33°, with latitude coverage only +/- $0\overset{\circ}{.}125$ i.e. total area 2 square degrees.

For methanol at 6.6 GHz, quite deep surveys with the ATCA cover the Galactic Centre, and a narrow Galactic plane strip, with longitude range 330° to 340° (Caswell 1996). Surveys with lower sensitivity, but with wider latitude coverage, are being conducted from Tasmania, with the first section already published (Ellingsen et al. 1996). Similar surveys from Onsala, and Torun are reported in this meeting.

To these can be added the element of unbiased surveying that occurs even in targeted surveys if the search is made with a quite large beamsize. For example, at the 6035-MHz transition of OH there have been no unbiased surveys, but the rare serendipitous detections unrelated to the targets of each search have given some indication of the scarcity of isolated masers of this transition (Caswell 1997). Similar considerations suggest that 12-GHz methanol masers in the absence of comparable 6.6-GHz maser emission are extremely rare.

Anderson & Genzel (1992) remarked that the maser community '....could have used....masers....to find sites of star formation by performing maser surveys....however, this has never been done....' But in reality, the above list shows that many such surveys have been performed, several of them predating Anderson & Genzel's remarks.

With that background, I will proceed to discuss what we know about the relationship between maser species at these sites. The increasing information from such studies makes it clear that masers are the major tool for studying these early stages of star formation, a fact that is now widely recognised.

I will be emphasising the 'typical' situation, for which we require large sample statistics to recognise the spread in properties. That then gives us a benchmark against which we can assess the unusual objects, and try to see what rare and special circumstances must be invoked to explain them.

Variability can both hinder and assist the study of relationships. It can mask correlations in intensities between species of maser, although, fortunately, only water masers seem to be a real problem in this regard. It can corroborate associations if correlated variations are seen (see Section 7).

4. General associations

Initial discoveries of OH and water masers towards strong radio continuum HII regions suggested that OH and water masers were coincident, and both associated with the HII regions. Precise measurements towards the archetypal SFR maser site, W3(OH) cast doubt on this view when they showed that the OH maser was indeed projected on to a strong UCHII region but the water maser was clearly at an offset position.

Was this common, or was it unusual?

A large sample of likely associations of OH with water were then investigated (Forster & Caswell 1989), and it was reassuring to find that many of the OH

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maser sites did indeed possess water maser emission from the same site. But additional water masers that were isolated were also found to be quite common.

Methanol masers, like water masers, considerably outnumber OH masers, but with the additional solitary methanol sites often situated close to a site hosting both OH and methanol.

So we come to the first relationship question - the general association - what can we learn from comparison of sites that occur within a cluster?

The example of 345.00-0.22 (Fig. 1) reveals a typical cluster of three maser sites, all within a region of extent less than 100 mpc. The UCHII region at one of the sites is crucial evidence that, for this site at least, we are dealing with masers associated with a very young massive star.

The occurrence of a cluster of sites is not surprising in a region where massive star formation is taking place. The two sites with no HII region have velocity similar to the main site, and quite small spatial separation from it, both facts strongly arguing that the additional sites are indeed of the same class as the one displaying all of the attributes of a young site of massive star formation. This is valuable since, in the absence of clues from other cluster members, it is sometimes not easy to identify the class of maser site. Water maser emission with no other evidence may simply arise in late-type stars. Ground-state mainline OH maser emission is also common amongst late-type stars. Neither are 1720-MHz OH masers unique to SFRs; when found in isolation they commonly are tracers of shocks in supernova remnants, as discussed later in this meeting. Interestingly, there are no indications that methanol masers of class II can occur in environments other than SFRs.

In other words, we learn that relationships at this general level of cluster membership can help us to confirm that each of the cluster sites is indeed of the variety associated with an embedded massive young, or embryonic, star.

We need now to explore which maser species can coexist at any maser site, and again illustrate the answer by returning to the field shown in Fig. 1. The principal site has methanol, a UCHII region, OH at 1665, 1667, 1720, and 6035 MHz, but no water. At smaller RA there is some even stronger methanol maser emission, water maser emission, weak OH, but no detectable continuum emission that might indicate an ultra compact HII region. To the north, there is yet another maser site, with water maser spots only. All pairwise combinations occur if we compare the transitions of methanol at 6.6 GHz, OH at 1665 MHz, and water at 22 GHz. Although none of the three sites of Fig. 1 has OH, methanol, a UCHII region and a water maser, there do exist some sites with all these properties, such as 355.344+0.147 (Caswell 1997).

Extensive comparisons of methanol with water showed that some of the methanol masers without OH coincided with water, and others were purely methanol masers. In both situations, the sites with no OH were found least likely to have detectable radio continuum UCHII regions.

But we have to keep this in perspective: deep searches towards OH masers show that only slightly more than half the masers have UCHII regions (Forster & Caswell 2000); in the case of methanol masers, this fraction drops below half, but is still substantial - as it must be, since 80 per cent of the OH masers have associated methanol maser emission.

There has been speculation that water masers tend to occur at a phase of star evolution earlier than the OH maser phase, although overlapping with it. But other characteristics of water masers include their occurrence in high velocity outflows, in regions no longer much influenced by the parent star, and so it is not surprising, given this propensity to mase under diverse conditions, that there are also water masers associated with quite low mass stars.

With this background, the fact that methanol masers, like water masers, considerably outnumber OH masers, immediately prompts the question as to whether this is predominantly because they occur at an earlier evolutionary phase, or whether their occurrence extends to the lower mass stars.

Fig. 1 diplays an example of a trend, where the site with methanol but no UCHII region has both the stronger methanol and the weaker OH, and its maser characteristics are thus 'methanol-favoured' (Caswell 1997).

Since the trend is found for many fields similar to 345.00-0.22, I have argued that, although the methanol 6668-MHz masers and the OH 1665-MHz masers often occur at the same sites implying a lengthy stage in the evolution of the massive star site that supports both species, there is, none the less, a tendency for the OH masers to survive to a later stage than the methanol, and for the methanol masers to begin at an earlier stage than the OH.

On this interpretation, the methanol/water maser pairs (with only weak, or no, OH) would most likely be at an early evolutionary state, predating the formation of UCHII regions (see also Forster & Caswell 2000).

5. Relationships or associations at the more detailed level

At any specific site, are the maser species segregated or intermingled, and do they share the same kinematics?

An early comparison for OH and methanol towards W3(OH) was made using VLBI maps, despite the difficulty of precise registration. Many more sites have now been investigated (Caswell 1997). For a sample of southern sources, I selected the 6035-MHz transition of OH for comparison with 6.6-GHz methanol. This circumvents several problems, including Zeeman splitting, since, for the 6035-MHz transition, the splitting is an order of magnitude less than for the 1665-MHz transition (if expressed as an equivalent velocity splitting). The two frequencies, 6035 and 6668 MHz, are also sufficiently close that we can achieve similar spatial resolution, and a common position calibration. Furthermore, if there is a UCHII region present, it can be used to check the position registration since it will be present with similar flux density at both frequencies. Finally, if there are optical depth effects where the HII region obscures the far side of any shell of emission, these effects will be similar at both frequencies.

Once again the example of Fig. 1 shows the typical result, with OH and methanol intermingled. From such intermingling, Hartquist et al. (1995) reach the important conclusion that the gaseous methanol and OH must originate from the evaporation of grain mantles.

Do all species tell the same story with regard to the combination of morphology and kinematics, indicative perhaps of rotation, discs, outflows, or shock-fronts? Overall, the OH and methanol often seem to do so, but interpretation remains controversial.

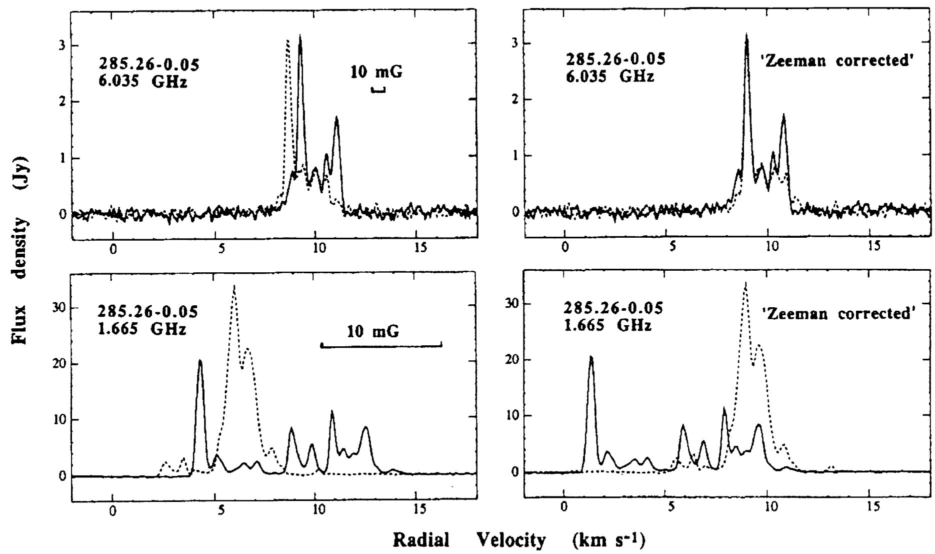

Figure 2. Observed spectra in LH panels show displacement of the 2 senses of circular polarization (LHCP broken line, RHCP continuous), attributable to the Zeeman effect. RH panels show the inferred velocities of emitted radiation when 'corrected' for Zeeman splitting.

Water has unique value in revealing special attributes such as high velocity outflows, rather than corroborating structures displayed by methanol or OH.

6. Comparisons between OH transitions at the most detailed level

Merely comparing the spectra of two transitions can sometimes be of considerable value, even in the absence of precise positional information.

For example, the site 285.26-0.05 (Fig. 2) shows no clear Zeeman pattern in the 1665-MHz transition. However the very clear Zeeman pattern at the 6035-MHz transition reveals how the 1665-MHz spectrum can be reinterpreted and found to show a similar magnetic field (Caswell & Vaile 1995), and strongly suggests that RHCP (right-hand circularly polarized) emission at 1665 MHz in the velocity range 0 to 5 km s^{-1} has no LHCP counterpart.

Fig. 3 shows the 6030- and 6035-MHz transitions towards 353.410-0.360 (6030-MHz emission from this source was first noted by Smits 1994). Both transitions display a prominent pair of RHCP and LHCP features, centred near velocity -22.1 km s^{-1} and separated less than 1 km s^{-1}, that appear to arise from Zeeman splitting, with a -9 mG field implied by both transitions. The significance of a slight misalignment in velocity is discussed later in this Section. The Fig. 3 single-dish spectra were taken while making long baseline observations, from which precise positional comparisons will eventually be possible.

It is not easy to achieve the high precision required to ascertain whether any of the maser spots of one transition coincide with those of another. Early exam-

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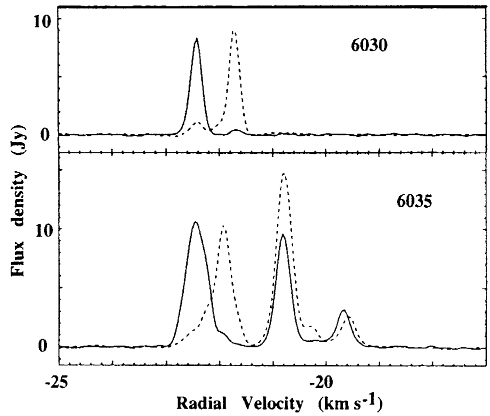

Figure 3. OH spectra observed 2001 Jan of 353.410-0.360, with RHCP shown as solid lines and LHCP as broken lines.

ples of high resolution long baseline measurements were made towards W3(OH). In these, it proved difficult to achieve precise alignment between the 1665- and 1667-MHz maps. Velocity comparisons encounter further difficulties because the apparent radial velocities of these transitions comprise not only a true velocity shift, but also a frequency shift imposed by the magnetic field through Zeeman splitting that is usually larger than the line width. Thus any true coincidences will be recognised only after correction for the Zeeman effect, but this is not possible unless both components of a Zeeman pair are detected, a condition that is rarely met for these transitions. The 'Zeeman problem' is absent from methanol and water, but remains if either of these species is compared with OH.

Fig. 4 shows a map of maser spots at 1665 and 1667 MHz for 323.459-0.079, with corresponding spectra at two positions. The observations were made with the long baseline array of the Australia Telescope (Caswell & Reynolds 2001). Both circular polarizations were observed simultaneously, with a bandwidth large enough to cover both the 1665- and 1667-MHz transitions. So we have precise spatial registration of transitions and polarizations. There are many discrete spots of emission, many of them showing coincident emision in both polarizations, indicating Zeeman pairs - some of them present at both transitions.

An effect noted for 6030- and 6035-MHz emission from 353.410-0.360 is also seen in the 1665- and 1667-MHz spectra of 323.459-0.079: there are unexpected slight discrepancies whereby matching Zeeman pairs appear on close inspection to be at slightly different velocities. The first suspect in such cases is the accuracy of the observations, and, second, the rest frequencies. Here, it seems that both are exonerated, leaving us to conclude that the emitting regions are indeed close, adjacent or overlapping, but there is a difference in velocity which may indicate that conditions gradually change to favour one transition rather than another. Similar effects were observed from comparisons of 1720-MHz with 1665-MHz and 4765-MHz transitions in W3(OH) by Masheder et al. (1994).

Instances where transitions occur in close proximity test theoretical pumping models. The observed coincidences of 1665- 1667- 6035- and 6030-MHz transitions are well accounted for by the Pavlakis & Kylafis (2000) pumping scheme,

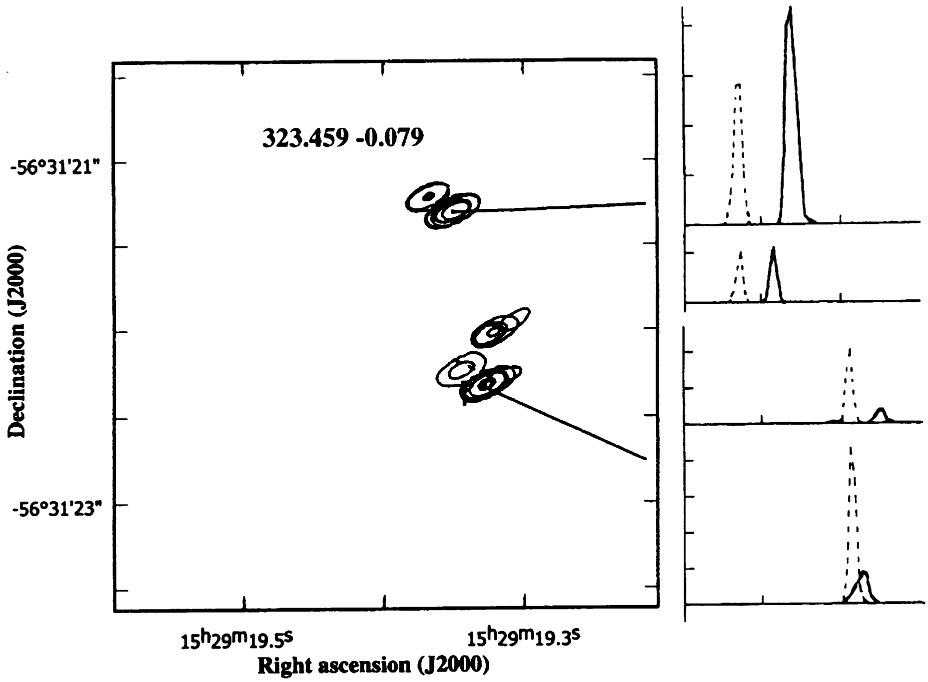

Figure 4. Maps of maser spots at 1665- and 1667-MHz in both senses of polarization overlaid. Small boxes display spectra at 2 positions where prominent Zeeman pairs occur. 1667-MHz spectra are shown beneath 1665-MHz spectra, with RHCP as solid lines, LHCP broken lines.

but expected to occur over only a very restricted range of physical parameters, so the maser effectively measures these parameters. 1720-MHz maser emission is predicted under 2 quite different situations; the high density variety at SFR sites (Caswell 1999) is quite distinct from that towards supernova remnants.

7. Comparisons between methanol transitions

In some respects, detailed spot comparisons for methanol are easier than for OH because there are no Zeeman effects to confuse direct comparison of velocities. But rest frequency uncertainties pose an additional problem. And spatial resolution high enough to confirm the coincidences, and preferably adequate to compare maser spot sizes, is not yet available for most methanol transitions.

Sometimes the emission from two or more transitions shows variations that are correlated (Caswell, Vaile & Ellingsen 1995), and further investigations of this type will be discussed elsewhere at this meeting by Gaylard and Goedhart.

In another type of study, Caswell et al. (2000) compare transitions at 107.0, 156.6, 6.6, and 12 GHz to assist in recognising weak masers, and distinguish them from confusing thermal emission. They find that the 107-GHz transition can be

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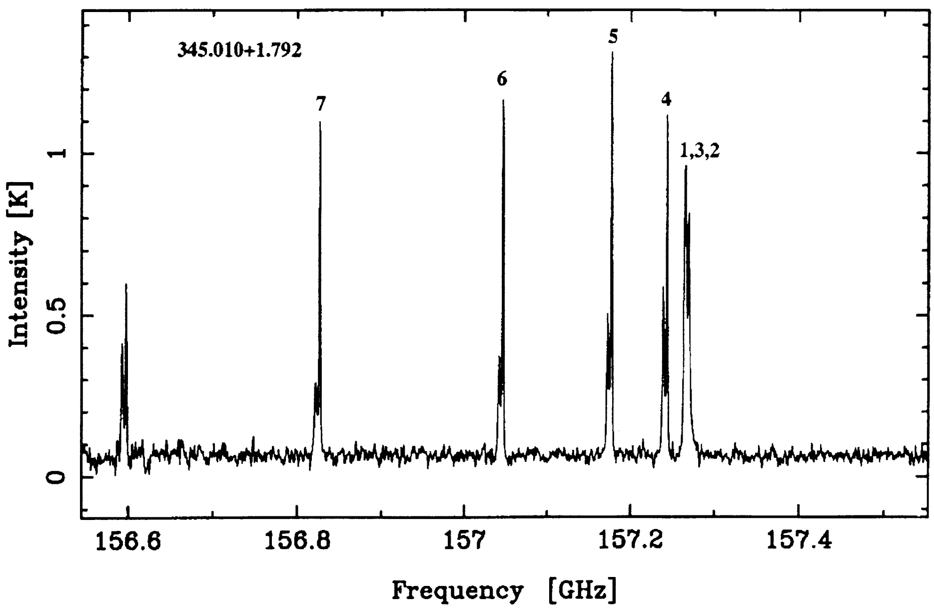

Figure 5. Methanol spectra towards 345.010+1.792 taken at SEST 2000 March. Numbers identify the value of J for transitions in the series J(0)-J(1) of E-type methanol. Emission near 156.6 GHz is from the 2(1)-3(0) A+ transition. At each J(0)-J(1) transition, the weaker feature is thermal emission, with intensity falling monotonically as J increases. The stronger feature is maser emission, with intensity showing a different functional dependence on J.

a quite strong maser, with weak thermal emission; the 156.6-GHz transition is usually a stronger thermal emitter, with much rarer weak maser emission. The conclusions based on velocity coincidence alone are quite persuasive that different species coincide, but precise positions will ultimately be needed.

Masing is sometimes found in the 157-GHz series of transitions of E-type methanol, transitions of the form J(0)-J(-1), where J runs from 1-8. This series is an extremely valuable probe for distinguishing thermal from maser emission, as was first shown by Slysh, Kalenskii & Val'tts (1995). Additional studies of this series have been made with SEST by Yi & Booth (in preparation), with a preliminary illustrative result shown in fig 5. From this site, 345.010+1.792, there is maser emission slightly displaced in velocity from thermal emission, each with a different dependence on J, and this difference has enormous potential as a diagnostic tool. Many southern sites have been observed at 157 GHz with large bandwidth to reveal trends such as seen here, and additional spectra have been taken at high spectral resolution to study individual transitions.

Of course, a comparison of the data with the pumping model can both refine the pumping model and yield estimates of the physical parameters such as density and temperature in the masing region, and this can be made better if there are even more transitions that have been measured as masing. A study of this type has been made by Cragg et al. (2001). In the case of 345.01+1.79 it is already possible to compare intensities of at least thirteen transitions. These comparisons yield some 'confirmation' of the correctness of the pumping model, or at least a consistency check, and also indicate what parameters of the model may require changes to fit the data. Thus the observed associations benefit the pumping models, and we obtain an excellent derivation of physical parameters if we assume coincidence and similar spot size, and seek a best fit of the relative intensity data to the model caculations.

Do methanol masers of class I sometimes coincide with those of class II? Generally not, and if we do find some that do, we should first reflect on the statistics: there are large numbers of each, present in the same general star forming environment. Occasionally there are likely to be spatial coincidences in projection, and perhaps even in velocity since the velocity is not a good distance discriminant within such regions. None the less, a true coincidence could reveal a short lived overlap phase.

Finally, are there any precise coincidences between OH and methanol? And if they are 'nearly coincident', what can we learn from this? This is a matter that needs further exploration on both the observational and theoretical fronts.

Another problem dominates this question if we extend comparisons to water masers: water maser variability is considerable, with the complete disappearance of some features and the birth of new ones at other velocities. In a sense this solves the problem, since it reveals that there is unlikely to be a close association of maser spots of water with those of the other less variable species.

8. Conclusions and future work

The relationships explored so far have been very productive, and justify considerable investment in similar studies in the future. In particular, extending the unbiased surveys is important, and will allow better recognition of the small number of contemporaneously forming stars within clusters. The increased samples will test the conclusions concerning the association of different species at the same sites, and whether these are indeed a clue to the properties of the putative embedded star - both its mass and its evolutionary state.

If we can classify the sites in this manner, perhaps it will reveal a clearer picture as to whether lines of masers trace discs or shock fronts in different evolutionary phases, and whether the spatial extent of the maser site is correlated with either the mass of the embedded star, or its evolutionary state; and likewise whether the velocity extent is correlated with such properties,

At the more detailed level, the coincidence of masing spots needs further exploration. We already have general association of methanol and OH showing them to be intermingled, which has been useful in suggesting the most likely origin of the molecules in this environment; now, it would be important if we could find some coincidences at a higher level of precision, since the pumping theory developments may soon be able to reveal their implications.

Within molecular species, there is already quite compelling evidence for precise coincidences, but these are quite rare, so each new discovery is very valuable. Such maser spot coincidences need complementary work on the measurement and comparison of spot sizes, such as is being pursued with the VLBA and the

EVN (Minier et al. 2001). In the case of OH, the allowance that must be made for different amounts of Zeeman splitting requires additional care, but yields the added bonus of even greater confidence in the magnetic field derivation.

And finally, the relationship to the IR objects is something that will become increasingly important as the IR observations improve. As is clear from the work described by de Buizer and by Walsh (this meeting), the initial results are encouraging but not yet unambiguous, and the potential for more valuable work is obvious as we progress to better observations at the longer wavelengths to elucidate more clearly what the IRAS data have hinted at. We may then expect improved confidence that we understand the precise mass range and evolutionary state of the embedded embryonic stars.

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References

Anderson N., Genzel R., 1992 in Astrophysical Masers, Proceedings, Arlington, Virginia. ed A.W.Clegg & G.E.Nedoluha (Lecture Notes in Physics v412 Springer Verlag), 97

Argon A.L., Reid M.J., & Menten K.M. 2000, ApJSuppl, 129, 159

Caswell J.L. 1996, MNRAS, 279, 79

Caswell J.L. 1997, MNRAS, 289, 203

Caswell J.L. 1998, MNRAS, 297, 215

Caswell J.L. 1999, MNRAS, 308, 683

Caswell J.L. & Haynes R.F., 1987, Aust.J.Phys., 40, 215

Caswell J.L. & Vaile R.A., 1995, MNRAS, 273, 328

Caswell J.L. & Reynolds J.E., 2001, MNRAS (in press).

Caswell J.L., Vaile R.A., & Ellingsen S.P. 1995, Pub.Astron.Soc.Aust., 12, 37

Caswell J.L., Yi J., Booth R.S., & Cragg D.M. 2000, MNRAS, 313, 599

Clegg A.W. & Nedoluha G.E. (eds) 1992, Astrophysical Masers, Proceedings, Arlington, Virginia. Lecture Notes in Physics v412 (Heidelberg: Springer Verlag)

Cragg D.M., Sobolev A.M., Ellingsen S.P., Caswell J.L., & Godfrey P.D., Salii S.V., Dodson R.G. 2001, MNRAS, in press

Ellingsen S.P., von Bibra M.L., McCulloch P.M., Norris R.P., Deshpande A.A., & Phillips C.J. 1996, MNRAS, 280, 378

Forster J.R., Welch W.J., & Wright M.C.H. 1977, ApJ, 215, L121

Forster J.R. & Caswell J.L. 1989, A&A, 213, 339

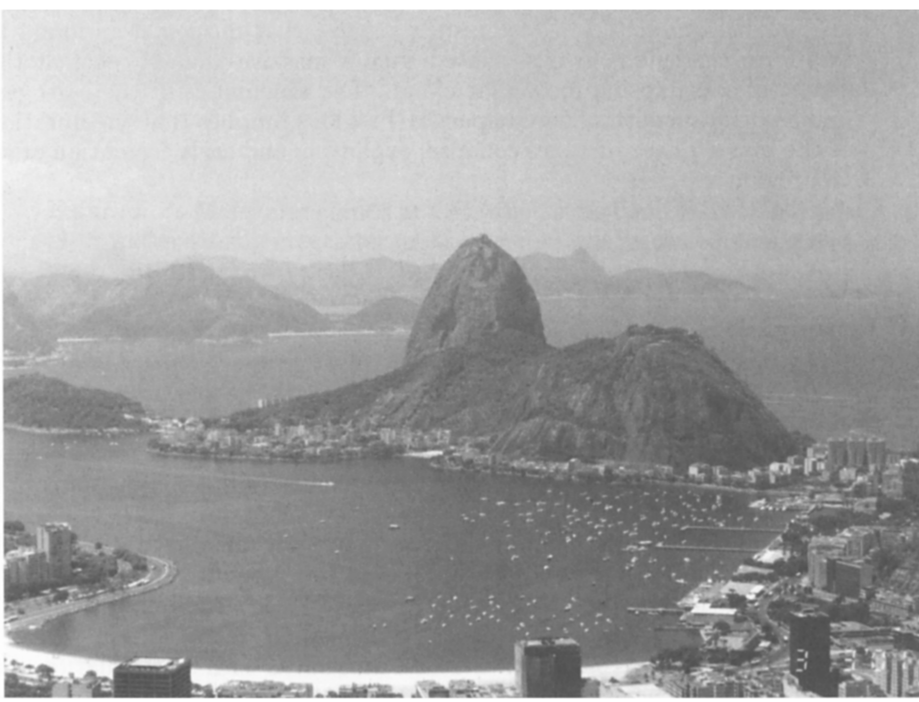
Forster J.R. & Caswell J.L. 1999, A&ASuppl., 137, 43

Forster J.R. & Caswell J.L. 2000, ApJ, 530, 371

Hartquist T.W., Menten K.M., Lepp S., & Dalgarno A. 1995, MNRAS, 272, 184

Masheder M.R.W., Field D., Gray M.D., Migenes V., Cohen R.J., & Booth R.S. 1994, A&A, 281, 871

Matthews H.E., Olnon F.M., Winnberg A., & Baud B. 1985, A&A, 149, 227
Menten K.M. 1991, ApJ, 380, L75
Minier V, Conway J.E., & Booth, R.S. 2001, A&A, in press
Pavlakis K.G.& Kylafis N.D. 2000, ApJ, 534, 770
Slysh V.I., Kalenskii S.V., & Val'tts I.E. 1995, ApJ, 442, 668
Smits D.P. 1994, MNRAS, 269, L11



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