RADIO OBSERVATIONS OF IR/OH/H_2O STARS

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Abstract. A small percentage of infrared stars, selected on the basis of their IR brightness at 2.2 μm and their redness ($I-K$ colour index), show 18 cm OH emission, and some exhibit 1.35 cm H_2O emission; further investigations identify some of these objects as M-type supergiants and the remainder as M-type giant long-period variable stars.

For the strongest 1612 MHz OH emitters, long-baseline interferometry shows that the emission arises from a large number of small-diameter features distributed over a much larger, approximately elliptical region corresponding to a circumstellar cloud. Models for the geometry of the emitting regions are discussed.

The OH characteristics with respect to the ratios of line intensities for different transitions and the velocity structure are distinctive, not being found in other types of OH source; consequently a large number of new OH emitters can be recognized as probably IR/OH objects despite the absence of IR or optical data; the precise classification of these sources is considered together with their relevance in understanding the identified sources.

I. Introduction

Shortly after the discovery of cosmic OH masers, infrared radiation was invoked as a possible source of the maser pumping; it was natural therefore to search for OH emission from the large number of objects found in the Caltech infrared survey at 2 μm (Neugebauer and Leighton, 1969). As a result, Wilson and Barrett (1968) detected OH emission with intensity greatest in the 1612 MHz transition from four IR objects, one of which, NML Cyg, proved to be the strongest OH emitter discovered to date. Subsequently a further class of OH emitter associated with IR objects was found with emission chiefly in the main lines at 1665 and 1667 MHz (Robinson *et al.*, 1971b). We will refer to both types of objects as IR/OH sources; they correspond to oxygen-rich M-type supergiants, and M-type giants, the latter group comprising long-period (Mira) variables (as shown by Hyland *et al.*, 1972).

H_2O emission at 1.35 cm has also been detected in the IR/OH sources, VY CMa showing strong H_2O emission and a number of other sources showing weaker emission (Schwartz and Barrett, 1970).

In the following sections we discuss the major characteristics of the OH and H_2O emissions, together with some of the closely related optical and infrared properties. The unidentified OH emitters of this type also give significant clues to our understanding of the objects.

II. Characteristics of the OH and H_2O Emission

It is convenient to follow Wilson and Barrett (1972) in treating the IR/OH objects as forming three classes according to their readily observed properties; in addition, we have treated as a separate class those OH sources with no IR identification but whose OH properties suggest they are IR/OH objects.

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(a) CLASS A. M-TYPE SUPERGIANT 1612 MHz OH EMITTERS

Only four objects in this class are known; they are listed in Table IA. The common properties, several of which can be seen in Figure 1, are:

(i) OH emission is strongest in the 1612 MHz line and occurs in two velocity ranges separated by about 50 km s^{-1}; in each velocity range the emission generally shows a gradual decrease of intensity in the direction of the other peak and a sharper decrease at the outer side. Little or no polarization is detectable.

(ii) Weaker 1667 and 1665 MHz (main-line) OH emission is present and may be highly polarized.

(iii) H_2O emission is observed in all four stars.

(iv) The 1720 MHz OH transition has not been detected.

(b) CLASS B. WEAKER 1612-MHz OH EMITTERS ASSOCIATED WITH M-TYPE GIANT LONG-PERIOD VARIABLE STARS

The 1612 MHz emission is similar to that of the supergiants but is 'scaled down' in

TABLE I

Positions and microwave properties of IR/OH stars

Name	Equatorial coordinates (1950.0)					Galactic coordinates		Peak intensity[a] OH emission		H_2O	References[b]
	R.A.			Dec.		l	b	1612 MHz	1665/7 MHz (Jy)	22235 MHz	
	h	m	s	°	′	°	°				
A. M-type supergiants											
VY CMa	07	20	55	−25	40.2	239	−5.1	230	140	10000	1, 2
VX Sgr	18	05	03	−22	14.0	8	−1.0	25	14	√	3, 4, 5
NML Cyg	20	44	34	+39	55.9	80	−1.9	520	13	80	6, 7
PZ Cas[c]	23	41	41	+61	31.0	115	−0.0	2.3		√	8, 9
B. M-type giant 1612 MHz OH emitters											
IRC+10011	01	03	48	+12	19.8	129	−50.1	37	3	–	10, 4
NML Tau	03	50	46	+11	15.7	178	−31.4	3	2.5	80	10, 5
IRC+50137	05	07	20	+52	48.9	156	+7.8	12	0.7	–	10, 4
IRC+40156	06	29	45	+40	44.9	174	+14.1	4.6	1.3	–	10
IRC−20197	09	42	56	−21	48.1	256	+23.3	7	0.7	–	10
R Crt	10	58	09	−18	03.6	269	+37.2	2	2	290	5
WX Ser	15	25	32	+19	44.1	30	+53.5	3	3	–	10
IRC+30292	16	25	59	+34	54.6	56	+43.5	3	–	–	10
IRC−10381	17	48	28	−08	00.7	19	+9.5	2.5	–	–	10
IRC−10434	18	30	30	−07	29.0	24	+0.6	2.5	0.8	–	10
IRC+10365	18	34	59	+10	23.0	41	+7.8	1.5	–	–	10
IRC−10450	18	37	35	−05	45.8	27	−0.1	3.4	–	–	10
R Aql	19	03	58	+08	09.2	42	+0.4	84	7.5	110	10, 4, 7
IRC−20540	19	05	56	−22	19.2	15	−13.6	12	√	–	10
RR Aql	19	54	58	−02	01.2	39	−15.6	5	2	19	10, 5
IRC−10529	20	07	46	−06	24.7	36	−20.4	35	8	–	10
UX Cyg	20	53	00	+30	13.4	74	−9.4	3	–	–	10
V Mic	21	20	37	−40	55.2	1	−45.5	8.4	1.9		11
IRC+40483	21	25	23	+36	29.0	84	−10.2	3.5	–	–	10

Table I (Continued)

Name	Equatorial coordinates (1950.0)					Galactic coordinates		Peak intensity[a] OH emission		H_2O	Refer-ences[b]
	R.A.			Dec.		l	b	1612 MHz	1665/7 MHz	22235 MHz	
	h	m	s	°	′				(Jy)		
C. Unidentified 1612 MHz OH emitters											
	16	37	30	−46	13.9	338	+0.1	5.1	–		11
	16	49	52	−41	43.8	343	+1.3	12	–		10, 4
	17	35	58	−32	10.3	356	−0.6	29	4	–	10, 4
[d]	17	50	02	−26	45	2	−0.3	4	–		12
	18	19	48	−12	53	18	+0.4	8			13
	18	21	17	−12	28.0	19	+0.4	26	2		10, 4, 14
	18	25	36	−10	13	21	+0.4	11			13
	18	26	48	−12	44	19	−1.0	16			13
W 41	18	31	27	−09	00.9	23	−0.3	12	–	–	4
	18	37	42	−05	00.6	27	+0.2	30	–		10, 4
	18	44	48	−02	39	30	−0.3	13			13
W 43*A*	18	45	05	−01	48.3	31	+0.0	55	2.5		4, 15
	18	45	54	−02	54	30	−0.6	55			13
	18	46	00	−01	51	31	−0.2	10	1		13
	18	48	48	−01	05	32	−0.4	7			13
	18	49	48	−00	18	32	−0.3	30	2		13
	18	54	56	+02	08	36	−0.3	18	1	–	4, 16
	19	11	54	+11	05	45	+0.1	11	–		13
ON 4	20	26	40	+38	57.0	78	+0.2	9	–	–	4, 17
D. M-type giant main line OH emitters											
R Hor	02	52	12	−50	05.6	265	−57.4	–	3.3	–	18
IRC+20082	04	26	07	+24	37.6	173	−16.3	–	0.7	–	19
U Ori	05	52	51	+20	10.1	189	−2.5	–	6	80	20, 21
R LMi	09	42	35	+34	44.6	191	+49.8	–	0.6	–	19, 22
W Hya	13	46	12	−28	07.1	318	+32.8	–	13	230	20, 7, 21
RU Hya	14	08	42	−28	38.4	323	+30.8	–	0.4	150	22, 5
S CrB	15	19	21	+31	32.8	49	+57.2	1.4	3	57	20, 21
U Her	16	23	35	+19	00.3	35	+40.3	–	3.5	330	7, 20, 21
IRC−20424	18	00	58	−20	19.5	10	+0.8	1.7	4	160	20, 5, 21
GY Aql	19	47	20	−07	44.3	33	−16.5	–	0.2	–	22
R Peg	23	04	08	+10	16.4	85	−44.6	–	0.4	70	22, 5
R Cas	23	55	53	+51	06.6	115	−10.6	–	3.5	56	20, 23

Notes to Table I

[a] Representative values from published profiles. Variability can be considerable – e.g., reported intensities for H_2O emission from VY CMa range from 1000 to 20000 Jy. No entry indicates absence of data; '–' indicates null result; '$\surd$' indicates positive detection but no details available.

[b] Basic radio data (positions, flux densities, line profiles) are referenced; more detailed studies are referred to in the text.

[c] Data from Kukarkin *et al.* (1969) indicate similarity with VX Sgr; wide separation of OH peaks ($\sim$55 km s^{-1}) is also characteristic of supergiants rather than giants.

[d] This OH source was found while pointing at the 100 μm IR source Hoffman 39 (no shorter wavelength IR counterpart has been reported); a chance coincidence is likely at this low galactic latitude, and the OH source is probably 'unidentified'.

References to Table I
1. Eliasson and Bartlett (1969).
2. Knowles *et al.* (1969).
3. Caswell and Robinson (1970).
4. Hardebeck (1972).
5. Dickinson *et al.* (1973).
6. Wilson *et al.* (1970).
7. Schwartz and Barrett (1970).
8. Dickinson and Chaisson (1973).
9. Dickinson (1973).
10. Wilson and Barrett (1972).
11. Caswell *et al.* (1971).
12. Chaisson and Dickinson (1972).
13. Winnberg *et al.* (1973).
14. Turner (1970a).
15. Robinson *et al.* (1970b).
16. Downes (1970).
17. Ellder *et al.* (1969).
18. Robinson *et al.* (1971b).
19. Wilson and Riegel (1973).
20. Wilson *et al.* (1972).
21. Hardebeck and Wilson (1971).
22. Fillit *et al.* (1972).
23. Turner and Rubin (1971).

both intensity and in velocity width (both in the separation of the peaks and widths of each feature). The main-line emission is also weaker and is sometimes not seen above the sensitivity limits achieved to date; H_2O emission is rather less frequently detectable and apparently confined to those sources showing main-line emission. Table IB lists sources in this category.

(c) CLASS C. UNIDENTIFIED 1612 MHz OH SOURCES WITH CHARACTERISTICS OF IR/OH OBJECTS

This group of sources we define as having the OH properties of Classes A and/or B, but they have been detected independently of known stars or of any prior IR search. It might be expected that a subsequent IR search would unambiguously group these with A or B, but in the few cases where such a search has been made IR emission is either absent or surprisingly weak; accordingly it seems desirable to define a separate category for these sources pending further study. Table IC lists these sources. With the addition of many new unpublished detections (Section VI), these now comprise the largest single group.

(d) CLASS D. IR/OH SOURCES WITH OH STRONGEST IN THE MAIN LINES (1665 AND 1667 MHz)

This class of source is associated with an IR object/M-type long-period variable star and shows OH emission strongest at 1665 or 1667 MHz. In some instances 1612 MHz emission is detectable, indicating no clear-cut division between Classes B and D (see Section IVc). A complex, possibly double-peaked, velocity structure is often recognizable, the velocity separation being less than that at 1612 MHz. H_2O emission is

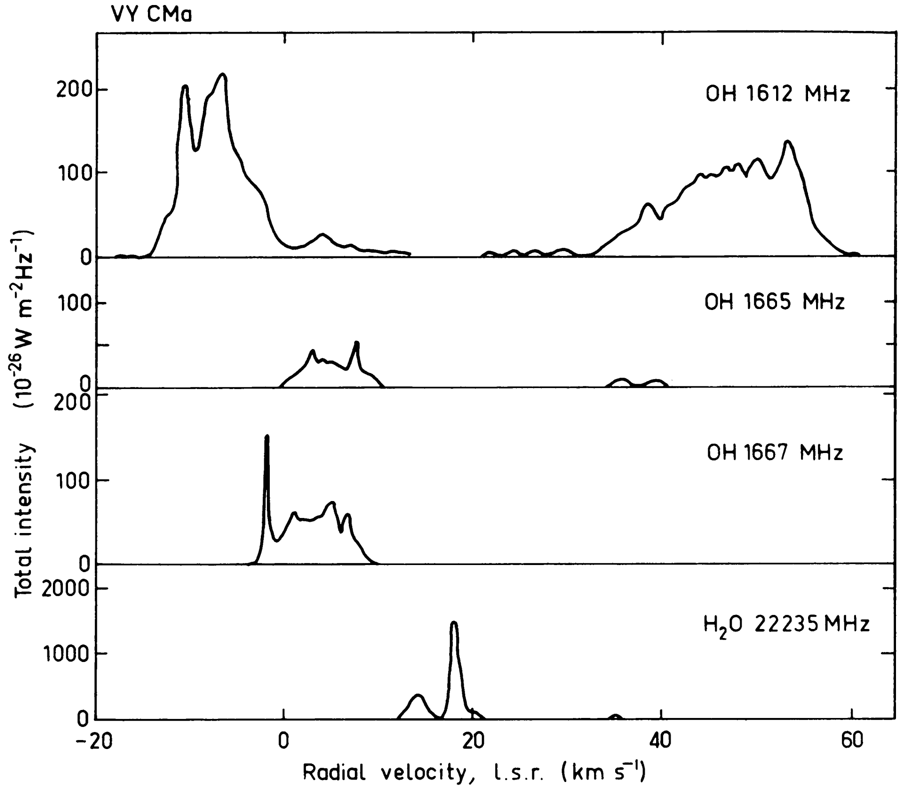

Fig. 1. OH and H_2O emission associated with the M-type supergiant VY CMa.

frequently detectable; again, the 1720 MHz transition has not been detected. Table ID lists the sources in this category.

III. More Detailed Study of Radio Properties

(a) THE CHARACTERISTIC 1612 MHz VELOCITY STRUCTURE

This is well shown in VY CMa (Figure 1). In this particular example the low-velocity feature has a greater intensity (both peak and integrated) than the higher (more positive velocity) feature. This is not a general characteristic, and of the 52 sources in Classes A, B and C for which data are available, approximately one-half (27) have the high-velocity feature more intense than the low-velocity feature, and within each individual group the fraction does not differ significantly from one-half. The histogram of Figure 2 shows the frequency distribution of the intensity ratio of the two features:

$$R = \frac{\text{Intensity of stronger feature}}{\text{Intensity of weaker feature}}.$$

We conclude that most commonly the features are approximately equal in intensity

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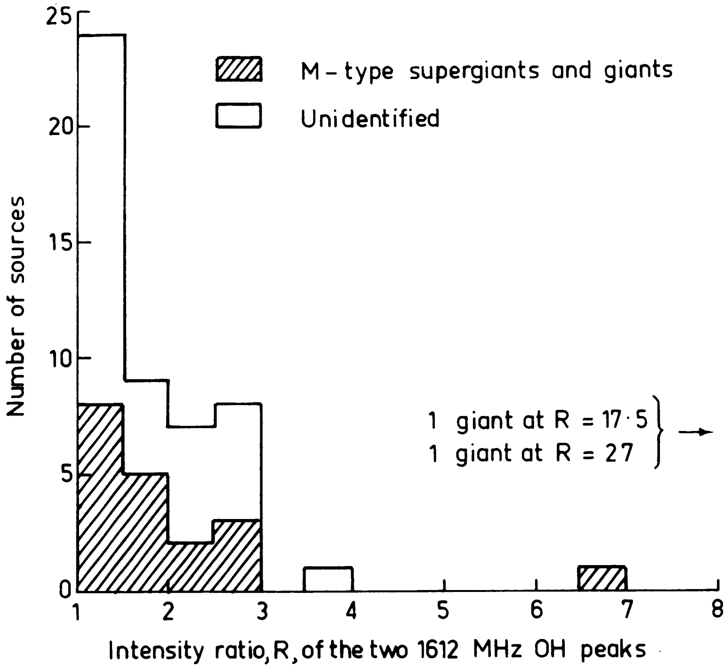

Fig. 2. The distribution of the intensity ratio, R, of the two 1612 MHz OH peaks for 52 sources. The median value of R is 1.7.

(both peak and integrated) with a steadily smaller fraction showing large ratios. Apart from UX Cyg, the distribution is complete for the identified sources and indicates that large ratios are rare. For UX Cyg only a single feature has been detected, probably because the sensitivity and/or velocity range of the observations was inadequate to detect the other feature. A number of single-feature unidentified 1612 MHz emitters have also been detected but probably only a few of these are double with high intensity ratios and at least some such objects do not belong to Class C; accordingly all single-feature unidentified objects are omitted from further study here (for example, OH 284.2–0.8 probably belongs to Class C, but OH 331.5–0.1 differs in several characteristics – see Caswell *et al.* (1971)).

(b) 1612 MHz ANGULAR STRUCTURE

Davies *et al.* (1972) have used long-baseline interferometry to derive the map of NML Cyg reproduced in Figure 3. In more recent work, Masheder *et al.* (1973) discuss further the NML Cyg results and present similar data for VY CMa; for both sources it is found that many individual emission features with diameters of only about 0.05″ are spread over a larger elliptical region of about 2″ and the positions of the low-velocity peaks are contained within a slightly smaller area than that covered by the high-velocity peaks. Over the total extent of the source, a gradient of velocity is observed which can be interpreted as indicative of rotation; however, it is important

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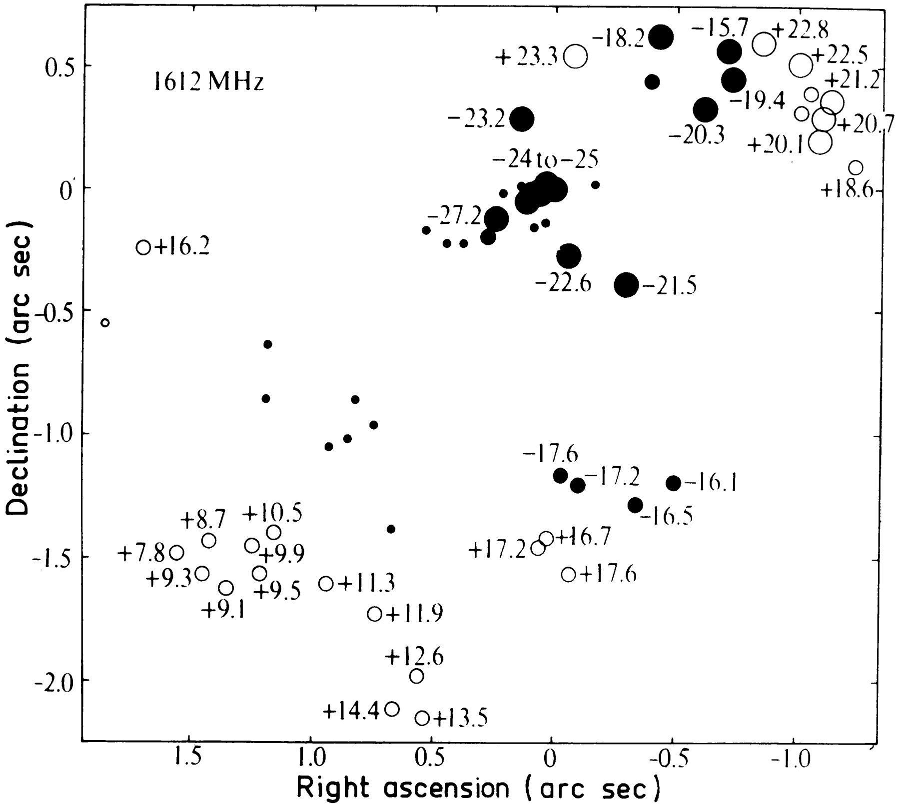

Fig. 3. The positions of the principal 1612 MHz OH features in NML Cygnus. Open circles indicate more positive velocity features; filled circles indicate more negative velocity features. Numbers indicate radial velocities (km s^{-1}) relative to the LSR (from Davies *et al.*, 1972).

to note that the map rules out rotation as the major cause of the double-peaked velocity structure. These data will be discussed further in connection with proposed models of the source (Section V).

(c) MAIN-LINE EMISSION AND WATER VAPOUR EMISSION

For Class A, B and C sources, two main-line emission peaks are sometimes present, with velocities usually just within the range of velocities of the 1612 MHz emission. Where only one main-line peak is present, it shows no preference for occurring at the high or low velocity, nor does it systematically accompany the stronger or the weaker 1612 MHz peak. The overall angular extent of the region emitting at 1665 or 1667 MHz is (for VY CMa, the only object studied to date) much smaller than at 1612 MHz (Harvey *et al.*, in preparation, quoted by Masheder *et al.*, 1973).

The 1665 and 1667 MHz emission from the supergiants VY CMa and VX Sgr contrasts with the 1612 MHz emission by showing both circular and linear polarization and also erratic variability in both intensity and polarization characteristics (Booth, 1969; Robinson *et al.*, 1970a; Robinson *et al.*, 1971a).

Main-line emission from Class D objects often displays a double-peaked velocity structure (Wilson *et al.*, 1972), but the central null is less distinct than that of the 1612 MHz emission in Classes A, B and C. Whether the main-line emission (in all four classes) is strictly similar to that of H II region emitters is not clear; for IR/OH objects the intensity of 1667 MHz emission is commonly comparable with or greater than that of 1665 MHz emission, whereas the converse is true of H II region OH emitters; in addition, the degree of polarization of 1665 and 1667 MHz emission is perhaps lower for IR/OH sources than for H II region OH emitters.

H_2O emission usually accompanies main-line emission in Classes A and D and sometimes also in Class B, but H_2O has not yet been detected in any Class B sources without detectable main-line emission. A number of long-period variable stars and IR sources have been found to show H_2O emission prior to any search being made for OH emission (Dickinson *et al.*, 1973; Dickinson, 1973); these are probably further examples of Classes A, B and D rather than a new class of object.

(d) TRANSITIONS OF OH IN THE EXCITED STATE

Several IR/OH objects have been searched for transitions in both the $^2\pi_{3/2}$, $J=5/2$ state and the $^2\pi_{1/2}$, $J=1/2$ state; a positive detection has been obtained only from the $^2\pi_{3/2}$, $J=5/2$ state for a single source, NML Cyg (Zuckerman *et al.*, 1972). With increased sensitivity, further study of the excited state transitions might assist in defining physical conditions within the sources.

IV. Comparisons with IR and Optical Data

(a) POSITIONS

The identifications of the OH/H_2O emitters with optical and IR stars are based on good positional agreements. Hyland *et al.* (1972) summarize new IR data and radio positions (the latter chiefly from Hardebeck, 1972) which indicate that for Class A and many Class B objects the agreement is very good; Hardebeck and Wilson (1971) show that positional agreement is good for several Class D objects.

Masheder *et al.* (1973) point out that, unfortunately, the absolute positional accuracy of their detailed OH maps is not sufficient to allow precise positioning of the stellar or IR object relative to the individual OH components.

(b) INTENSITY VARIABILITY

In the infrared, some sources such as NML Cyg show little or no variability, while others such as CIT 3 show variation of several magnitudes. The infrared variability allows some objects with no detectable optical counterpart (because of obscuration) to be unambiguously classified as Mira variables. The 1612 MHz OH emission exhibits slow periodic variations apparently paralleling the optical and infrared changes (Bechis *et al.*, 1971; Hardebeck and Wilson, 1971) and corroborating the identifications. The percentage modulation of the OH intensity is always less than that of the infrared or optical emission.

The main-line OH emission and the H_2O emission have also been reported to show systematic long-term variability (in addition to the more erratic variability noted earlier) for all classes of source.

Dickinson (1973) concludes, on the basis of a new search for water-vapour emission, that the Mira variables most commonly showing H_2O emission are those which show the greatest change in visual magnitude.

(c) INTENSITY AND COLOUR OF ASSOCIATED *IR* OBJECTS

We will merely summarize an interpretation and list the supporting evidence.

For OH emission at 1612 MHz and on the main lines, and for water-vapour emission, an appropriate cool M-type star is required – an inference made from the correlation of the presence of all three emissions with the colour index $I-K$ (Hyland *et al.*, 1972).

The main-line OH emission often found in Class B objects will be considered together with that of Class D objects; its detectability is correlated with K magnitude (Wilson *et al.*, 1972), and since K magnitude is a satisfactory distance indicator for this type of star the correlation indicates that only nearby objects are detected and that the luminosity of main-line OH emission is generally low. Furthermore there must presumably be a quite low scatter in maximum main-line luminosity in order for the correlation to be recognizable. The fact that objects with detectable main-line OH emission are local is reflected in the large scatter in galactic latitude which they display (the mean $|b|$ for main-line emitters in Tables IB and ID is $\sim 28°$).

The detectability of H_2O emission is correlated with that of main-line emission, showing that it requires similar physical conditions. However, the intensity of H_2O emission is more sensitive to small changes in these conditions (as is also indicated by its generally more extreme time variability); it thus has a large range of luminosity which weakens any correlation with K magnitude (Dickinson *et al.*, 1973).

1612 MHz emitters are best regarded as a sub-class of the main-line emitters; the very wide range of 1612 MHz luminosity which they exhibit results from a strong dependence on the presence of a circumstellar dust cloud (inferred from an IR excess in the wavelength range 10–20 μm). The wide range of luminosity destroys any recognizable correlation with distance, i.e., with K magnitude (Wilson and Barrett, 1972). Because of its wide range of luminosity 1612 MHz emission is not detectable in many of even the nearby main-line emitters (Class D objects), while at the other extreme it may be an order of magnitude stronger than main-line emission so that for high-luminosity 1612 MHz emitters at large distances *main-line* emission is not detectable; the mean value of $|b|$ for Class B emitters with no detectable main-line emission is only 13°, consistent with their being objects more distant than those showing main-line emission.

(d) OH VELOCITY COMPARISONS WITH OPTICAL AND *IR* DATA

The optical spectra of M-type supergiants and M-type giant long-period variables usually show an emission line spectrum. For about half the stars studied an absorption spectrum has also been measured, displaced from the emission to more positive velocities. In the few IR/OH sources for which optical data exist, the emission and absorption velocities correspond approximately with the more negative and more positive velocity 1612 MHz peaks, respectively (see Table 3 of Wilson and Barrett, 1972). A similar correlation is found for main-line emission (Wilson *et al.*, 1972). However, the optical velocities in some cases change considerably during the light cycle (cf., e.g., Feast, 1963), whereas to a high degree of precision (better than 1 km s^{-1}) no velocity changes have been detected in the OH velocities, so that the correlation must be treated with caution.

Optical observers of long-period variable stars have noted a correlation of $A-E$ (the separation of the extreme velocities) with period (cf., e.g., Feast, 1963); since $A-E$ appears to correspond with the separation of the peaks of 1612 MHz OH emission, it is to be expected that a plot of the latter against period will show a similar correlation; furthermore, for this investigation it is possible to use infrared periods even where no optical data are available. Dickinson and Chaisson (1973) verify that such a relation appears to hold.

The separation in velocity of the OH peaks is also correlated with redness (or dust-shell thickness) for both 1612 MHz and main-line peak separation (Wilson *et al.*, 1972), i.e., the shell is expanding with a velocity approximately proportional to the dust-shell thickness. It might be expected that since the dust shell appears to be a prime requirement for 1612 MHz emission, the luminosity of 1612 MHz emission would in turn be proportional to the peak separation, but this is not readily seen above the scatter, although there is some suggestion of its validity in that intense 1612 MHz emission from supergiants has a wider velocity separation than that from the weaker giants.

V. Models of the Sources

The models proposed so far are very preliminary. They have been designed to fit the supergiants for which more data are available but would be expected with little change to apply to Class B sources also.

For VY CMa, a source for which a large amount of optical and IR data exist, Hyland *et al.* (1969) explain the infrared excess in terms of a circumstellar dust cloud and give appropriate model parameters. The OH emission can be fitted into this picture in a variety of ways. However the more negative velocity ('blue-shifted') OH peak is generally assumed to arise from the near side of an expanding shell.

In both the models to be mentioned here, the more positive velocity OH peak is assumed to be at the stellar velocity, by comparison with optical absorption data (Merrill, 1940). Davies *et al.* (1972) suggest that it arises in the same shell as the more negative velocity emission, but at the periphery as projected along the line of sight, where the expansion is merely a tangential motion. The intensity distribution as a function of radial velocity (showing a central minimum) is not an immediate consequence of the model but the angular distribution of the emission is accounted for satisfactorily. Dickinson *et al.* (1973) suggest the data could be better accounted for if a shock-front is invoked with the smaller area of 'blue-shifted' emission being due to its containment within the shock-front and the 'stationary' (more positive velocity) gas being external to it.

Essentially Davies *et al.* (1972) emphasize that the area covered by the more negative velocity peak is smaller than that covered by the more positive velocity peak, while Dickinson *et al.* (1973) emphasize that it is not very much smaller. The absence of high-velocity emission in the central region (in angular extent) is necessary to the Davies interpretation but is irrelevant to the Dickinson interpretation. For neither model is it clear why the far side of the shell, with a still greater red shift, should not be seen; Davies *et al.* suggest free-free absorption by ionized gas, optically thick at 18 cm, within the OH emitting shell; this hypothesis might be contradicted if no continuum emission from the absorbing cloud could be detected at high frequencies. In the direction of ON-4, an upper limit to the continuum flux density of 1.5×10^{-3} Jy at 1400 MHz has been reported by Baars and Wendker (1973). Turner (1970b) cites continuum interferometer measurements at 2700 MHz yielding upper limits of 10×10^{-3} Jy for NML Cyg and VY CMa. At 5000 MHz an upper limit of 20×10^{-3} Jy for VY CMa has been obtained (Caswell, unpublished); for this source Wilson (1971) has reported a tentative detection ($200 \pm 70 \times 10^{-3}$ Jy) at 3.5 mm which still lacks confirmation. Goss *et al.* (1974) have recently reported the detection of a continuum source with $S(10.7\text{ GHz}) = 12 \pm 2 \times 10^{-3}$ Jy coinciding with NML Cyg to within 30″. Information on its angular extent and spectrum is necessary to determine whether it possesses the properties required to fit the model of Davies *et al.* (1972)

General OH and H_2O maser pumping mechanisms have been discussed by Turner (1970b) whereas Litvak and Dickinson (1972) present a pumping mechanism designed to account specifically for IR/OH objects; any refinements will probably require a better understanding of the physical geometry of the sources.

VI. The Unidentified Sources

The unidentified sources of Table IC constitute 'accidental' discoveries (while studying other objects) together with objects found in a *survey* at Onsala (Winnberg *et al.*, 1973).

None of the objects has been found to coincide with a known late M-type star or with a previously catalogued IR source. Although an IR source has subsequently been discovered in the direction of ON-4, apparently it is weak and has properties unusual for OH/IR objects (Wilson and Barrett, 1972). The IR source which Glass and Feast (1973) propose as an identification with OH 338.5+0.1 is probably not associated, since a remeasurement of the OH position (Caswell and Haynes, unpublished data) confirms a separation of more than 2′. It is clearly very important to achieve the maximum possible positional accuracy for the OH sources in order to allow sensitive searches for related optical and IR objects.

The mean value of $|b|$ for unidentified sources in Table IC is 0°.4. These sources have been discovered largely in searches confined to low galactic latitudes, but it should be noted that no unidentified sources have been found in several hundred search positions at higher latitudes during either the Wilson and Barrett (1972) or the Caswell *et al.* (1971) search of known IR objects. We infer that the small value of $|b|$ for unidentified sources would not be increased much if systematic surveys were extended to higher latitudes and we note that such a small value of $|b|$ is characteristic of distant supergiants. In contrast, objects of Class B have a median value of $|b| \sim 20°$, characteristic of Mira variables, as noted by Wilson and Barrett (1972).

The velocity separations of the 1612 MHz emission peaks in the case of unidentified sources are characteristic more of the long-period variable giants than of the supergiants (Winnberg *et al.*, 1973).

Overall, we conclude that although the unidentified objects have OH properties similar to both the supergiants (Class A) and the giants (Class B), they are not merely unidentified members of either class but probably represent a new class in their own right.

Figure 4 shows a velocity-longitude diagram for Class A, B and C objects in which the velocity plotted is that of the more red-shifted peak. The Class B objects (M giants)

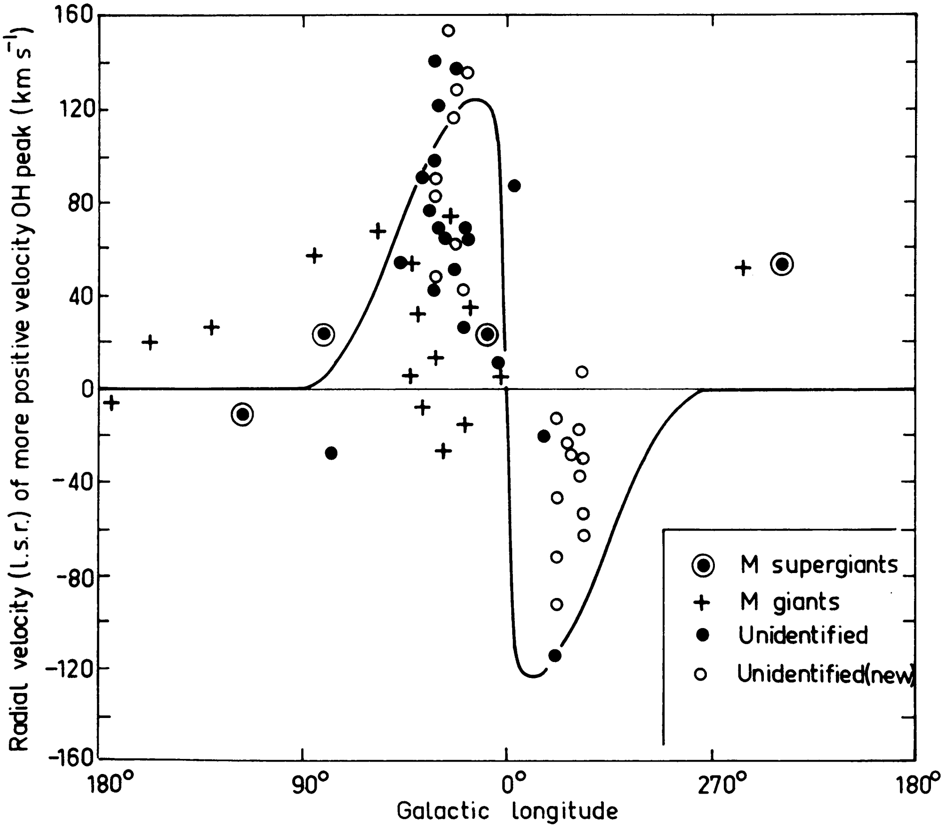

Fig. 4. Velocity-longitude plot for 1612 MHz IR/OH emitters; the radial velocity plotted is that of the more positive velocity OH peak. The curve indicates the maximum velocity 'allowed' on the Schmidt galactic rotation model. Unidentified (new) sources are unpublished results from the Onsala survey and a new survey by Caswell and Haynes (see text).

are relatively nearby and have no significant velocity component arising from galactic rotation but show a quite high scatter in their random velocities – both positive and negative. For the unidentified objects published to date in the longitude range 0° to 50° no objects show negative velocities while three show velocities greater than the maximum 'allowable' on the Schmidt (1965) galactic rotation model. Wallerstein (1973) infers from the distribution in velocity of the published Onsala unidentified sources in this region that (a) they are more like supergiants at large distance and (b) the true velocity representing the stellar motion may be midway between the OH peaks.

We have added a number of new unpublished sources to study this situation further. In the longitude range 18° to 33° there are nine additional sources from the Onsala search (Winnberg *et al.*, private communication) and 12 sources in the range 327° to 340° have been added from a new low-latitude survey of 1612 MHz OH emission by Caswell and Haynes (unpublished). In the region 18° to 33° the absence of negative velocities results partly from less coverage of this velocity range, but the survey by Caswell and Haynes extended to velocities of $+130 \text{ km s}^{-1}$ so that the striking absence of positive velocity sources in the region 327° to 340° is real and significant. The velocities range from zero to the maximum 'allowed'; since at least some of the objects would presumably be nearby, the absence of positive velocities at longitudes 327° to 340° (and the absence of negative velocities at longitudes 18° to 50°) implies a small velocity dispersion. Where large velocities are observed, they are presumably due to galactic rotation and indicate large distances. We conclude that the objects are more like supergiants in their kinematic properties and it is reasonable to use the characteristic velocities to infer kinematic distances. This important conclusion appears inescapable.

In the longitude range 18° to 33° six sources exceed the maximum 'allowed' velocity whereas none does so in the longitude range 327° to 340°. No such striking asymmetry is evident in the H I distribution (Kerr and Hindman, 1970). In Figure 5 we have replotted the velocity-longitude diagram using the mean velocity of the two OH peaks, instead of the more positive of the two velocities. It is seen that this produces a much greater degree of symmetry (or more precisely, antisymmetry) about $l = 0°$, particularly for the unidentified OH sources. This plot suggests interpreting the mean velocity as representing the motion of the star; such an interpretation would not be consistent with the models considered previously but would allow a much simpler explanation of the two OH emission peaks in which they arise from near and far sides of an expanding shell. It was shown in Section III that, statistically, in their widths and intensities and their accompaniment by main-line emission, the more positive and less positive velocity 1612 MHz OH peaks are not distinguishable; this symmetry also favours the simple expanding-shell model. (We might also note that a contracting rather than an expanding shell would be equally acceptable for the OH interpretation.) Problems arise chiefly with the optical interpretation because, for a few of the identified objects, the more positive velocity OH peak corresponds fairly well with the optical absorption velocity near maximum light which in turn is customarily assumed to represent the characteristic stellar motion (see Section IVd).

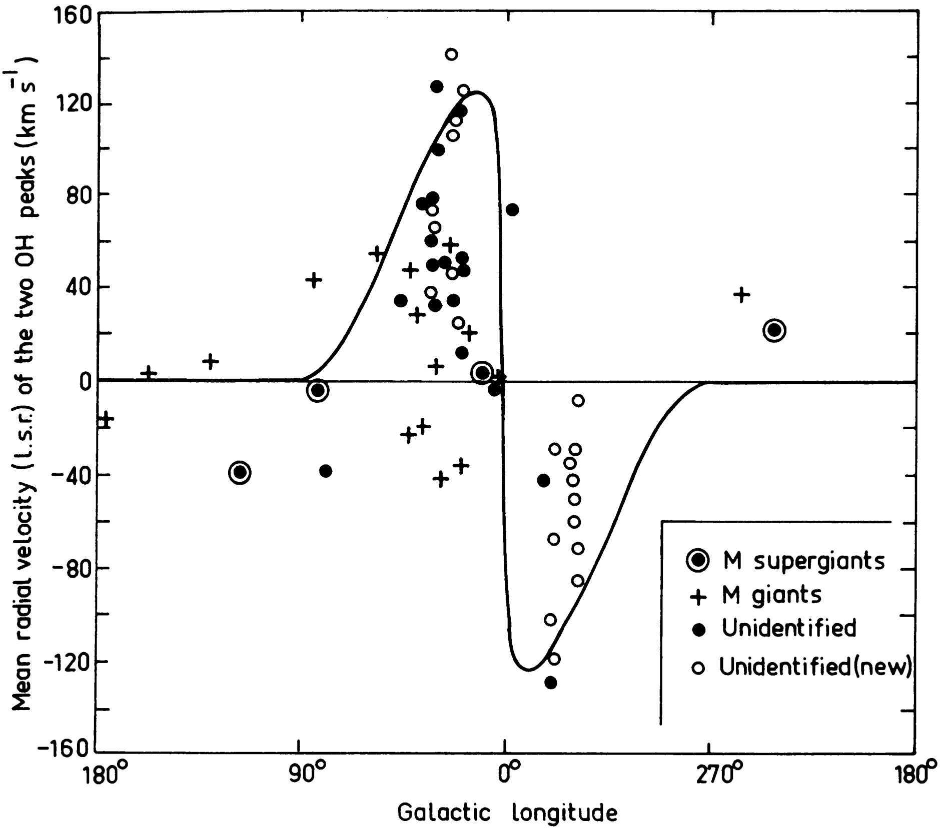

Fig. 5. Velocity-longitude plot for 1612 MHz IR/OH emitters; the radial velocity plotted is the mean of the two OH peaks.

VII. Conclusion

IR/OH stars commonly show weak main-line OH emission: the 1612 MHz OH emitters appear to represent a sub-class satisfying more stringent conditions – in particular a long-wavelength IR excess which probably provides the maser pump and which arises from a prominent circumstellar dust shell. The 1612 MHz emitters have well-defined general characteristics, and some sources have been studied in detail, but the correct geometrical model for the 1612 MHz emitting region remains a problem. A solution to this problem is suggested by the unidentified sources which support a simple expanding shell model in which the two major velocity peaks of 1612 MHz emission arise in near and far sides of the shell. The apparent conflict with optical interpretations which caused an earlier rejection of this model now merits further investigation.

The unidentified 1612 MHz OH sources constitute the largest class of IR/OH objects and represent a rapidly growing area of study; identification of these objects with IR stars is of major importance, since preliminary unsuccessful searches for identifications suggest that the amount of IR radiation needed to produce the 1612 MHz emission is less than for the identified objects.

With a better understanding of these aspects of 1612 MHz emission, viz. the geometrical model and the role of the IR radiation, there would be good prospects for solving the long-standing problem of a detailed pumping mechanism for OH maser emission.

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DISCUSSION

Palmer: First, how do you sort out which of the many main line emitters fit into your classification D; and second, does Orion fit into your classification scheme?

Caswell: I define Class D OH emitters as being associated with known IR objects, generally identified as M-type giant long period variables. Since the OH characteristics of Class D sources do not differ markedly from those of main line emitters associated with H II regions, no attempt has been made to see if any of the latter fit better into Class D. Orion does not fit into any of the classes discussed here.

Batchelor: How do the OH velocities compare with the stellar velocity?

Caswell: The more negative velocity peak corresponds approximately with the optical emission velocity and the more positive velocity with the optical absorption velocity; the latter is usually interpreted as representing the characteristic velocity of the star.

Barrett: A unique OH source was recently discovered by Lo and Bechis. The source appears coincident with V1057 Cyg and radiates at 1720 MHz in two features of flux density 48 and 34 Jy. The width of the features is ~ 0.3 km s^{-1}, and the separation is ~ 0.35 km s^{-1}. Both features show elliptical polarization of $\sim 25\%$. Emission or absorption at 1612, 1665 and 1667 MHz was not detected at a level of 0.7 Jy.

Zuckerman: Because the OH emission was observed with a single antenna it is dangerous to associate it with V1057 Cyg. A similar identification of an unusual OH source with the planetary nebula NGC 2438 turned out to be incorrect after an interferometric position was obtained for the OH source.