THE INFRARED PROPERTIES OF CIRCUMSTELLAR OH/IR AND H_2O/IR SOURCES

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Abstract. Anomalous OH and H_2O microwave emission is a common occurrence in circumstellar shells surrounding cool oxygen-rich M supergiants and Mira variables. Infrared spectra have shown that the atmospheric conditions in these stars are such that the concentration of OH molecules is a maximum. For those with H_2O microwave emission, strong H_2O 1.9 μm absorption is present.

There exists a growing number of typical OH/IR sources discovered by radio surveys, for which no associated IR object has yet been found. Preliminary results of TV photography to discover IR counterparts are shown.

Several interesting correlations have been defined between the IR colour, period and amplitude of infrared variability, and the velocity separation of the OH emission peaks. The relationship of these to pulsationally driven mass loss and the observed characteristics of circumstellar dust shells is investigated.

The maser emission from OH/IR and H_2O/IR sources is believed to be pumped by IR radiation. Combined studies of the variability of OH and H_2O emission and the IR continuum of the Mira sources confirm that IR pumping is probably the dominant mechanism, although the data do not appear to favour any specific pump scheme. The OH masers are at least partially saturated; the degree of saturation of the H_2O masers is unclear.

I. Introduction

Since the association of certain microwave OH emission sources with stellar infrared sources was discovered several years ago (Wilson and Barrett, 1968; Eliasson and Bartlett, 1969), microwave, infrared and optical studies have established the general pattern of relationships which exist between the properties observed in different parts of the spectrum. The basic microwave characteristics of the OH/IR sources have been derived from the investigations of Wilson *et al.* (1970), Wilson and Barrett (1972) and Robinson *et al.* (1970, 1971). These may be summarized as follows:

(i) The OH emission may be strongest in (a) the 1612 MHz satellite line (the Turner [1970] type IIb sources, often called simply the 1612 MHz sources) or (b) the 1665/1667 MHz mainlines (the type I or mainline emitters).

(ii) The emission occurs in two main ranges of velocity separated by between 5 and 60 km s^{-1}. Where optical data are available, the more positive velocity peak corresponds reasonably well with the stellar absorption-line velocity, while the more negative peak agrees well with velocities derived from stellar emission lines. The OH profile peaks are usually narrow, though in a small number of cases (specifically, those identified with M supergiant stars) the 1612 MHz emission occurs in two broad features.

(iii) The OH emission is weakly polarized.

(iv) No emission has been detected at 1720 MHz, nor (with the exception of NML Cyg) has any continuum source been detected at the location of OH/IR sources.

As a result of a very recent investigation by Harvey *et al.* (1974), a further important characteristic should be added to the above.

(v) The OH emission often varies in a regular manner by factors of 2–4 in intensity, in phase and with the same period as the infrared variations.

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It has also been shown (Schwartz and Barrett, 1970) that a number of microwave H_2O sources are also associated with infrared sources and late M stars, and that in several cases these are also OH sources. For these the H_2O emission velocity peaks generally lie between those of the OH emission, and the H_2O emission is often highly variable.

Combining the microwave characteristics with the optical and infrared studies of Hyland *et al.* (1969, 1972) and Wilson *et al.* (1972), a simple picture has been developed (relevant to both OH/IR and H_2O/IR sources) which encompasses the basic observations and is a convenient starting place for a review of the known infrared properties of such systems. Each system is considered as being composed of three main parts (shown schematically in Figure 1).

(i) A central stellar source which is either an M supergiant star or long-period variable M star with an effective temperature lying in the range $1800\ \mathrm{K} < T_* < 2600\ \mathrm{K}$.

(ii) A circumstellar shell of gas and dust which emits predominantly in the infrared and which has a characteristic temperature $T_s \sim 600$–700 K. (For simplicity all circumstellar shells are considered here to be spherical.)

(iii) A further circumstellar shell of gas which includes the OH and H_2O emitting regions and which may be partly or wholly co-extensive with the dust shell (ii), but which at least in two cases (NML Cyg and VY CMa) is approximately 10 times larger (see, e.g., Davies *et al.*, 1972). Dynamically it is currently thought that the circumstellar shells are expanding at a steady rate indicative of the rate of mass loss from the central

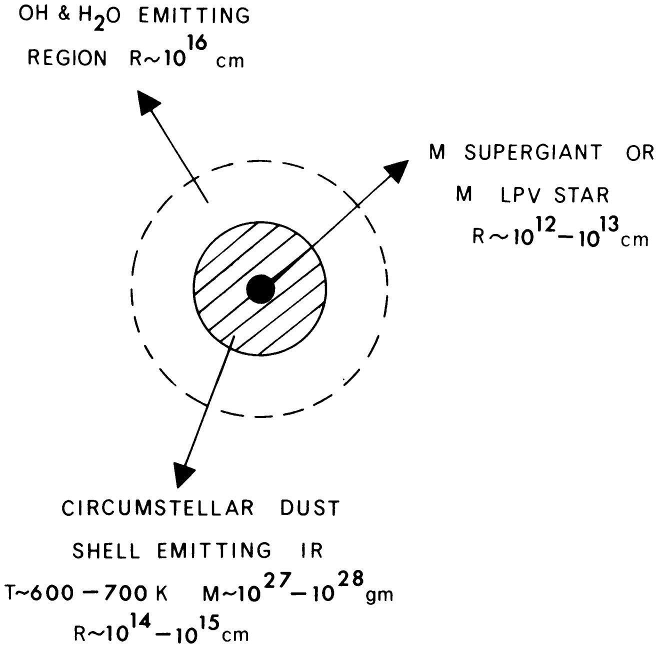

Fig. 1. A schematic representation of the main components of an OH/IR source with typical dimensions.

source, while from considerations of the possible maser processes it is widely believed that the OH and H_2O molecules are pumped by infrared photons.

In this review the available infrared observations are discussed insofar as they relate to (a) OH and H_2O systems as a whole, (b) any one of the individual components described above or to (c) questions of radiative pumping and any correlations of properties which may help to bring the phenomena together in a coherent manner.

II. The Identification of OH/IR Systems

For historical reasons most surveys for OH/IR sources have been conducted by searching at the positions of known infrared sources, and these have proved eminently successful (see, e.g., Wilson *et al.*, 1970; Wilson and Barrett, 1972). More recently OH and H_2O emission has been sought successfully by searching at the positions of long period variable M stars (Schwartz and Barrett, 1971; Caswell *et al.*, 1971; Nguyen-Quang-Rieu *et al.*, 1971).

The identity of the microwave and infrared sources was established for several cases by the interferometric observations of Hardebeck (1972) and Hardebeck and Wilson (1971), positional agreement being obtained to better than 15″. A few accidentally discovered OH sources with the right characteristics have remained unidentified with any known infrared source.

Discoveries of OH/IR and H_2O/IR sources certainly differ from other radio surveys because of the unusual search technique which has been used, and consequently there are large selection effects inherent in the discoveries. The situation is presently being rectified somewhat by comprehensive sky surveys along the galactic plane. Winnberg *et al.* (1973) and Caswell and Haynes (1973) have already discovered a large number of sources with characteristics similar to the supergiant OH/IR sources. The most interesting feature of these recent results is that in no case is there any obvious IR source which can be identified with the microwave source. The possibility exists that these may be a new class of OH emission source, or at the very least the relationship of the intensity of microwave to infrared emission differs considerably from that of the well known sources.

To settle the question as to the nature of these new sources, it is important for infrared surveys to be undertaken in conjunction with the OH surveys to search for possible infrared counterparts. The common method of scanning the microwave error boxes at infrared wavelengths is time consuming unless the OH positional accuracy is high. This method has been used to locate infrared identifications for ON-4 (Neugebauer, quoted by Winnberg *et al.*, 1973) and G338.5+0.1 (Glass and Feast, 1973). However, no details are known regarding the characteristics of the former, and the latter identification has been challenged because of the lack of positional and velocity agreement.

A faster technique has been used by the author for searching for IR sources which holds promise for future identifications of OH/IR sources. The region to be searched is photographed through blue and infrared filters with a TV camera (SEC vidicon,

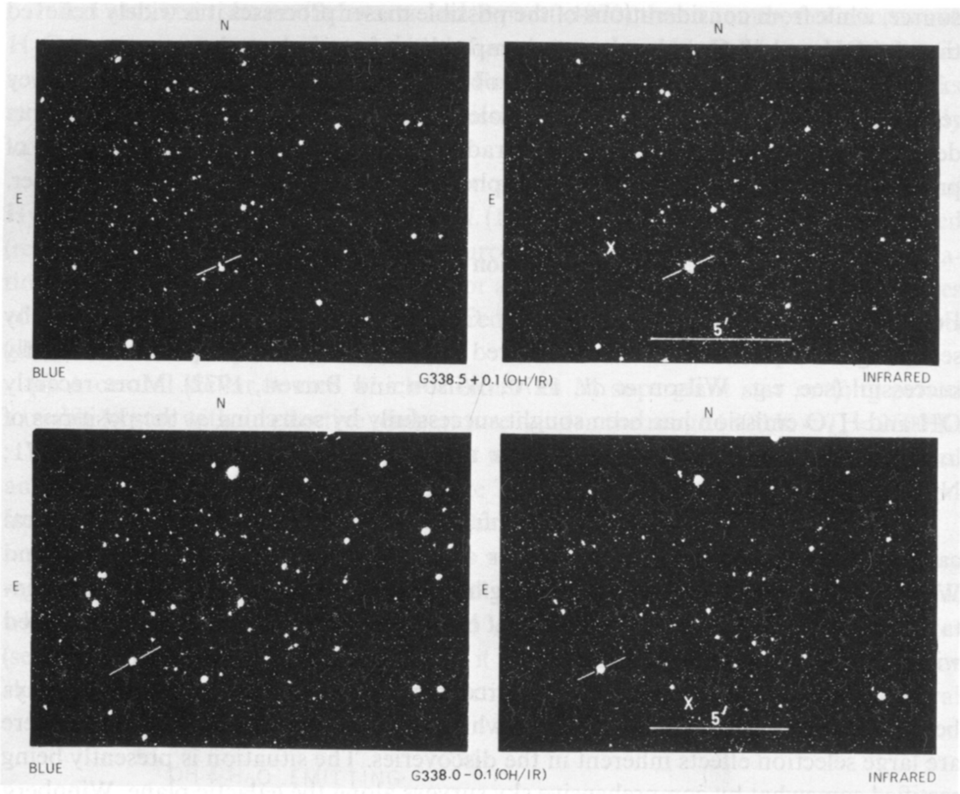

Fig. 2. Blue and infrared television photographs of the regions near the two sources OH338.5 + 0.1 and OH338.0 − 0.1 as described in the text. The OH positions are marked by a cross on the infrared frames, and the nearest infrared sources are marked.

S-25 photocathode) attached to the cassegrain focus of a 16 in telescope, and which gives a visible field of $\sim 15 \times 10'$. The filters and photo-cathode response provide effective wavelengths corresponding approximately to the $B(\lambda 4300$ Å) and I_{Kron} ($\lambda 8000$ Å) bands. Two examples of this technique are shown in Figure 2 where (a) the infrared source found by Glass and Feast (1973) is shown in comparison with the OH position for G338.5 + 0.1 and (b) the region near OH 338.0 − 0.1 is shown. There is an infrared source $\sim 2'$ east of the OH position in (b), but the positional agreement is too poor for this to be claimed as an identification.

This technique is clearly applicable to searches for infrared counterparts of OH sources. Typically for an integration time of 2.5 s, a limiting magnitude $I_{\mathrm{Kron}} \sim 14$ can be reached, and this corresponds to a 2.2 μm magnitude $K \sim 6$ for the very reddest known objects. Such a search thus effectively extends the limit of the reddest known infrared sources some 3 mag fainter than that of the Caltech Two Micron Sky Survey (Neugebauer and Leighton, 1969).

III. Spectroscopic Observations and the Nature of the Central Stellar Sources

It has been firmly established from both optical and infrared spectra that the central sources of OH/IR systems are M supergiants and M-type long-period variable stars. The stars associated with microwave H_2O emission sources belong to the same categories, although irregular variables of late M spectral type have also been found to be H_2O emitters but not OH emitters (e.g., RX Boo). Because a large number of the OH/IR sources (in particular the 1612 MHz sources) are bright in the infrared, but very faint visually, the most comprehensive spectroscopic data has been obtained from infrared spectra in the 2 μm region (Hyland *et al.*, 1972; Frogel, 1970). From these spectra, which include most of the identified OH/IR and H_2O/IR sources, the following general features can be noted.

(i) Three of the strongest 1612 MHz OH sources (which are also microwave H_2O sources), NML Cyg, VY CMa and VX Sgr, have been classified as late M supergiants. The major characteristics of their spectra are the strong absorption due to the first overtone CO vibration rotation band and the presence of weak but visible H_2O absorption between 1.7 and 2.0 μm. These characteristics are illustrated by the spectra of VY CMa and VX Sgr in Figure 3. It is notable that the spectra of earlier supergiants (none of which has yet been found to have microwave OH or H_2O emission lines) show no absorption due to H_2O at the resolution available.

(ii) The majority of the 1612 MHz OH/IR sources have infrared spectra characteristic of the long-period variable (Mira) M stars; i.e., they have both very strong H_2O absorption in the broad 1.9 μm and 2.7 μm bands and moderate to strong CO absorption. The spectra of two typical examples of this class are also shown in Figure 3. In extreme cases (such as IRC+10011 shown) the continuum may be affected by absorption and re-emission of radiation by the circumstellar dust particles; however, the effect is not large enough to affect the classification of the central source to any marked degree.

(iii) Infrared and optical spectra of the mainline OH/IR sources, and the H_2O/IR sources show that these are also generally long-period variable M stars. No distinguishing spectroscopic features have been found by which one can separate these from the 1612 MHz sources. Three examples of such spectra are shown in Figure 4. S CrB is both a mainline OH source and an H_2O emitter, RX Boo is an H_2O source, and IRC-20424 is an unusual mainline OH emitter which will be discussed further in the next section. Hyland *et al.* (1972) have emphasized that the unique contribution of the infrared spectra is that estimates of the effective temperatures and abundance characteristics (especially the oxygen to carbon ratio) of the central sources can be obtained *independently* of interstellar or circumstellar reddening. The conclusions of their study of 1612 MHz sources are also applicable to the mainline OH emitters and the H_2O sources, and are:

(α) All the central stellar sources have photospheric temperatures which lie in the limited range 1800 to 2600 K. For conditions typical of the photospheres of luminous M stars this is the very temperature range at which the partial pressure of OH reaches

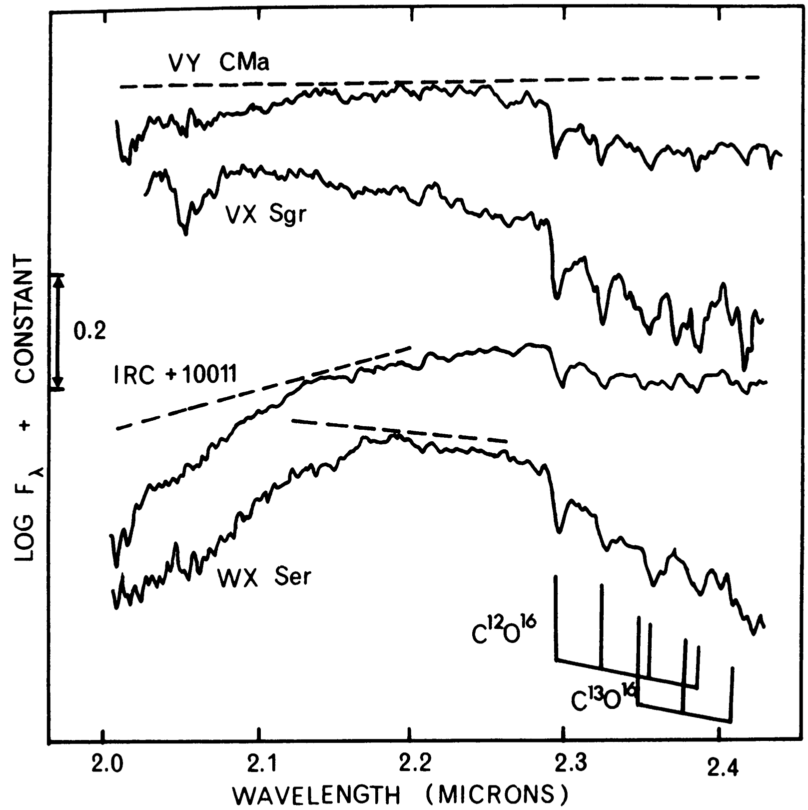

Fig. 3. Infrared spectra of the supergiant OH sources VY CMa and VX Sgr and the 1612 MHz long period variable sources IRC + 10011 and WX Ser are shown. F_λ is the normalized flux per unit wavelength interval. The dashed lines indicate the slope of the continuum as determined from broad band photometry. The spectra are notable for the strong absorption by CO beyond 2.3 μm and for absorption by H_2O molecules between 2.0 and 2.15 μm.

a maximum (see, e.g., Tsuji, 1964). At a given photospheric pressure this peak in the partial pressure of OH is very sharp; a change of 200 K either way produces a decrease in the partial pressure by more than an order of magnitude. Additionally, the partial pressure of H_2O lies within a factor of 3 of that at total association.

(β) All stars associated with OH or H_2O emission have oxygen-rich photospheres. No carbon stars, where $O/C < 1$, or S stars, where $O/C \sim 1$, have been identified with OH or H_2O sources.

Hence, the photospheric layers of all the OH and H_2O microwave sources are rich in OH molecules and H_2O molecules, and Hyland *et al.* have suggested that the molecules responsible for the microwave emission originate in these photospheres and remain associated as they are driven outwards into a circumstellar shell where the conditions for maser emission become favourable. Further direct evidence linking stellar mass loss and microwave emission will be discussed in the next section.

All the available infrared spectroscopic data has been obtained at medium resolu-

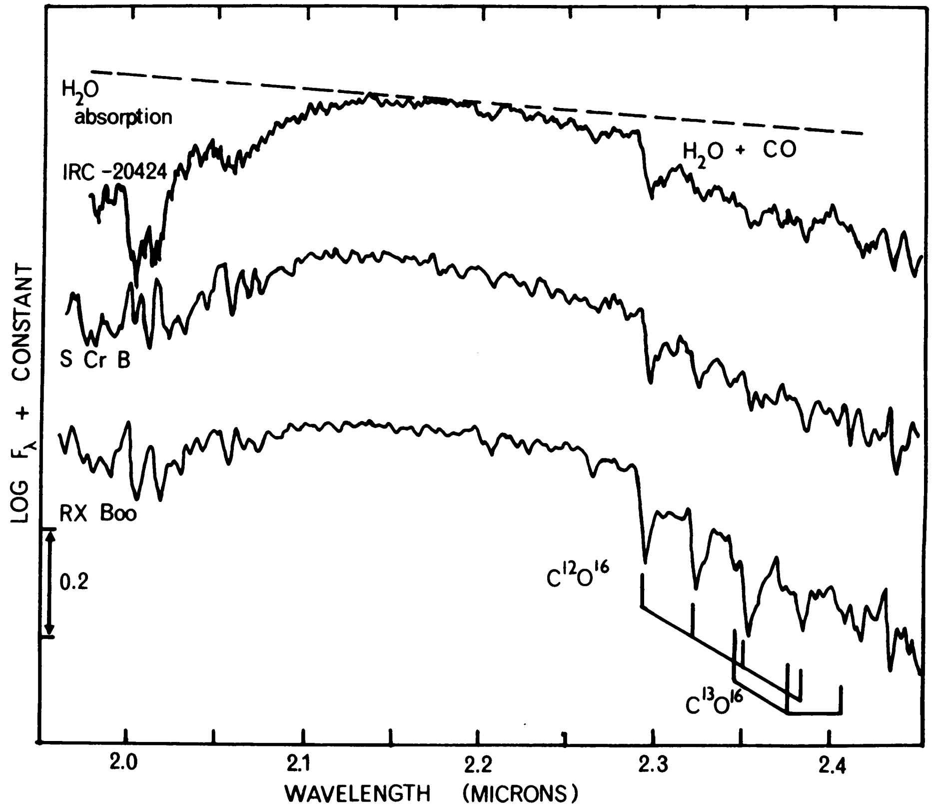

Fig. 4. Same as Figure 3. IRC-20424 and S CrB are long-period variable 1665/1667 MHz emitters. S CrB and the irregular M8 giant RX Boo are microwave H_2O sources.

tion, and no direct measurements have been made on the individual molecular lines, in particular those of CO, H_2O and OH, which are available for study at high resolution. Some very recent work at high resolution in the 1 and 2 μm region has been reported (Maillard, 1973) and holds great promise for detailed investigations into the photospheric properties of the M giant and supergiant OH/IR stars. Maillard obtained evidence from one star (R Leo) of a splitting of the individual CO lines into two components at one phase of its variation. The velocity difference agreed well with that found for the separation of the OH emission peaks. Curiously, he found no evidence for the splitting of the measurable infrared OH lines! The continuation of such high-resolution studies can be expected to provide exciting results necessary for the understanding of the relationships between pulsation and mass loss, and for deriving more realistic models for OH/IR sources.

Few optical spectroscopic studies of OH/IR sources have been reported in the literature (Hyland *et al.*, 1969; Wallerstein, 1971). Their major contribution has been in the determination of the optical velocity systems for comparison with the OH emission velocities. The general results obtained from these and other published velocities of long-period variable M stars (Feast, 1963) are that the more positive velocity OH peak corresponds approximately with the stellar absorption line velocity, while the more negative velocity peak is in reasonable agreement with the optical emission line velocity. A summary of the available velocity data has been given by Wilson and Barrett (1971). The situation regarding the equality of OH emission velocities and optical velocities is not, however, clear cut, since it is known that photospheric velocities vary by 5 km s^{-1} or more during the cycles of long-period variable stars. It is necessary therefore to have accurate observations around a cycle to be able to determine the stellar systemic velocity. Programmes of this nature are highly desirable. Furthermore, optical velocity studies are of prime importance for the positive identification of the stellar counterparts of the unidentified high velocity sources recently discovered along the galactic plane (Winnberg *et al.*, 1973).

IV. Infrared Photometry and the Properties of the Circumstellar Dust Component

In the simple picture of OH/IR sources described in the introduction, the central stellar source was considered to be embedded in a large circumstellar shell of dust and gas, which determined to a large extent the infrared properties of the source. Infrared photometry between 1 and 20 μm provides information both about the circumstellar component and the central stellar source.

(a) STATISTICS OF THE NEAR INFRARED COLOURS

These have been obtained from the extensive 1612 MHz survey of Wilson and Barrett (1972) which included 403 stars selected from the Caltech Two Micron Sky Survey, and have been discussed by those authors and Hyland *et al.* (1972). The main conclusion is that *all* 1612 MHz OH/IR sources have 0.8 – 2.2 μm colours $[I-K]>4.6$. Since 140 infrared sources included in the survey had values of $[I-K]<4.6$ this is unlikely to be due to selection effects and essentially corroborates the spectroscopic analysis, which showed that all OH/IR sources have photospheric temperatures lower than 2600 K.

(b) INFRARED EXCESSES AND COLOUR DIFFERENCES BETWEEN THE 1612 MHz SOURCES AND MAINLINE EMITTERS

From observations covering the wavelength range 1.25–20 μm, Hyland *et al.* (1972) showed that almost all the 1612 MHz sources possess large infrared excesses and that they were among the very reddest stars found in the Two Micron Sky Survey. The majority of those stars with large infrared excesses but which did not exhibit OH emission were found to be carbon stars. The infrared excesses of the 1612 MHz OH/IR sources have been generally interpreted in terms of circumstellar dust shells with characteristic temperatures between 600 and 700 K which absorb the visual and near infrared radiation and re-radiate the energy at longer wavelengths. This widely accepted model can be used to derive useful information regarding the structure of such shells and will be discussed below.

While the 1612 MHz (supergiant and type IIb) OH/IR sources generally possess large infrared excesses, Wilson *et al.* (1972) and Hyland, Hirst *et al.* (1972) have shown that this is not the case for the mainline (type I) OH/IR sources. The distinction between the two groups of sources is illustrated in Figure 5, where histograms of the number of sources in a given 2.2–3.5 μm $(K-L)$ colour interval and 2.2–10.2 μm $(K-N)$ colour interval are shown. Both colours are representative of the dust shell structure, the former representing the stellar continuum as modified by the absorption properties of the dust particles, the latter representing the low temperature dust shell emission.

The histograms show that mainline emission predominates in those sources with the bluest colours, i.e., those for which there is little evidence for the presence of circumstellar dust particles. On the other hand 1612 MHz emission increases as the optical depth of the circumstellar dust increases and dominates the other lines when the shell is optically thick at near infrared wavelengths. Wilson *et al.* (1972) have also shown that the 10.2–20 μm colours, which depend on the extent of dust at temperatures ~300 K, are also correlated with the OH type in the same sense.

Mention should be made of the two unusual sources which complicate the simple picture, R Aql and IRC-20424. The former is a strong 1612 MHz source which possesses no dust shell characteristics, while the latter is a mainline emitter which has a large infrared excess, typical of the 1612 MHz sources.

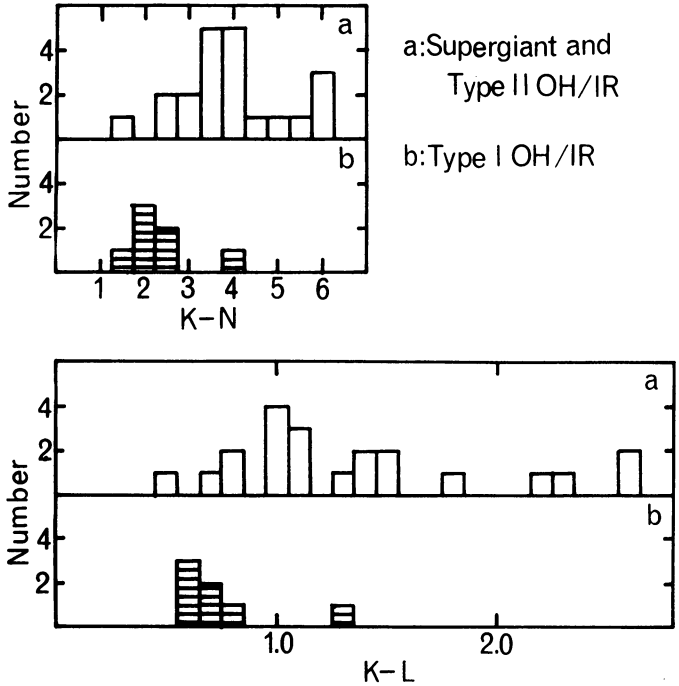

Fig. 5. Histograms of the number of OH/IR sources in a given colour interval. The distribution with colour of the type I (mainline) OH/IR sources is seen to be different from that of the type II (1612 MHz) sources in the sense that the former are significantly bluer in both the $K-N$ and $K-L$ colours.

The existence of these anomalous cases suggests that although the presence and extent of circumstellar dust particles are important in determining the characteristics of the OH emission, a further important parameter as yet unidentified must also be taken into account.

(c) SHELL STRUCTURE

It is widely accepted that the large infrared excesses such as those of the 1612 MHz sources are the result of absorption and re-emission processes by circumstellar dust particles. For a few sources (e.g., VY CMa, VX Sgr) spectroscopic data in the 8–14 μm region confirm the presence of an emission feature which can be attributed to emission by silicate-like particles (e.g., Gillett *et al.*, 1970). The observations show, however, that the excess emission clearly extends to wavelengths as short as 4.8 μm.

Only the simplest models have been applied in any systematic way in the literature. Models have been constructed by Hyland *et al.* (1972) for the case of a central star with $T = 2200$ K surrounded by an isothermal dust shell in which the absorption coefficient of the dust at short infrared wavelengths was assumed to have a λ^{-1} dependence. Figure 6 shows that the colours derived from these models adequately describe the observations of the OH/IR sources. Again a fairly clear separation between the 1612 MHz sources and the mainline emitters is seen. From these simple models the majority of sources appear to have dust shells with temperatures in the range 600–700 K. The percentage of the observed flux which is re-radiated emission from the shell is also shown in the figure. Although the implications have not been fully explored, the large number of 1612 MHz sources with optically thick dust shells and the lack of any visually unreddened sources with large infrared excesses suggest that the assumption of spherical symmetry is not grossly in error. However, further investigation of models where the assumption of spherical symmetry has been relaxed, such as that advanced by Herbig (1970), would appear to be needed at this stage.

Typical properties of the dust shells have been derived (Hyland *et al.*, 1972), and a few examples from their paper are shown in Table I. Typically the shell radii range between 5×10^{14} and 10^{15} cm, and the dust shell masses between 2×10^{27} and 1.5×10^{28} g, where these values are based on source luminosities at maximum of 10^4 $L_{\odot}$. Correspondingly, the optical depths at 1.65 μm range from $\tau = 0$ for R Aql and several mainline emitters to $\tau = 2$ for IRC+10011.

TABLE I

Typical shell characteristics of OH/IR sources

Object		$\frac{L_{\text{shell}}}{L_{\text{total}}}$	T_{shell} (K)	R_{shell} (10^{15} cm)	M_{shell} (10^{27} g)
M supergiants	VY CMa	0.75	600	1.5	15
	NML Cyg	0.75	600	1.5	15
Long-period	IRC+10011	0.85	700	0.5	3
variable M	WX Ser	0.30	500	1.0	2
stars	R Aql	0.05	–	–	–

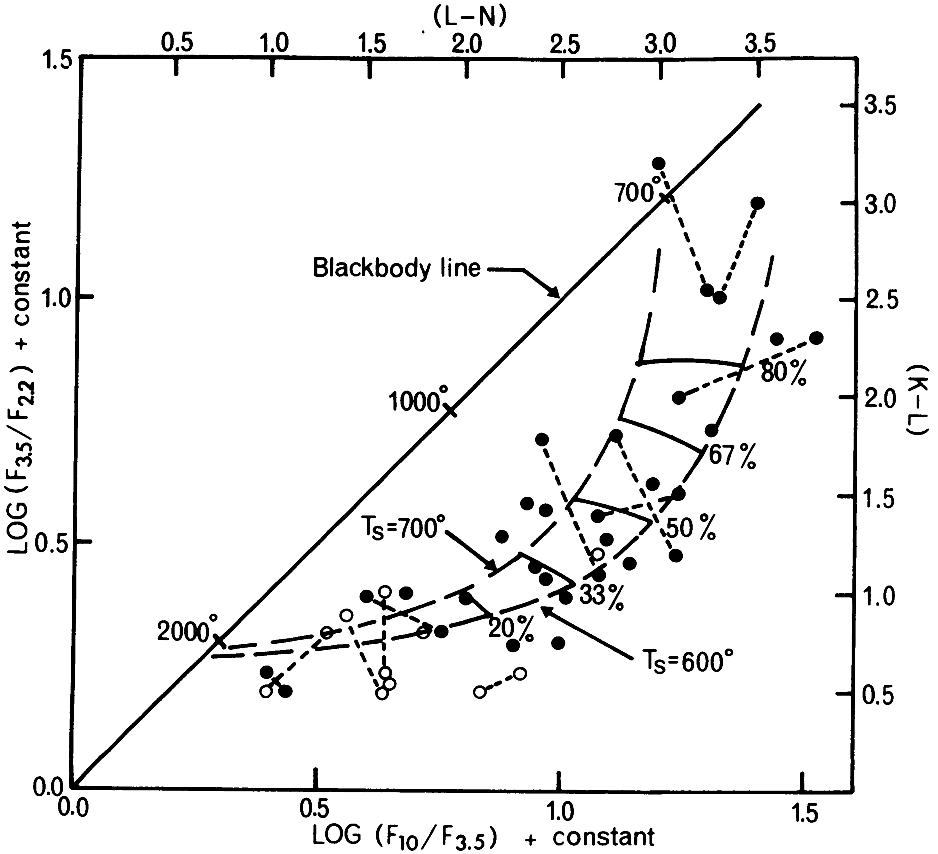

Fig. 6. Flux ratios at 10.2 and 3.5 μm and at 3.5 and 2.2 μm are compared for both 1612 MHz (filled circles) and 1665/1667 MHz (open circles) OH/IR sources. The diagonal line corresponds to the flux ratio for black bodies at the temperatures marked. The dashed lines correspond to dust shells of temperatures of 600 and 700 K surrounding a central star with photospheric temperature of 2200 K; the solid lines joining the dashed curves show the fraction of the total energy emitted by the shell. R Aql is the 1612 MHz source at the extreme lower left edge of the distribution and IRC-20424 is the lone 1665/1667 MHz source in the middle of the region dominated by 1612 MHz emitters. The small dashed lines join extreme values of the flux ratios observed during the cyclical variations of the long-period variable sources.

(d) SHELL STRUCTURE AS A CONSEQUENCE OF MASS LOSS

The association of 1612 MHz sources with thick circumstellar dust shells and the one to one correlation of the (photospheric) molecular abundances lead to the suggestion of a common mass ejection process for the dust shells and the OH and H_2O molecules responsible for the microwave emission. Although attractive, this idea has not been universally accepted, e.g. Davies *et al.* (1972) suggest that in the case of NML Cyg the circumstellar material is the remnant of a protostellar dust cloud. Evidence in favour of the common mass ejection hypothesis may be summarised as follows:

(i) Direct evidence for mass loss from the photospheres of long-period variable M stars is derived from the differential velocities of the absorption and emission lines

(Merrill, 1960; Feast, 1963). In the case of the M supergiants VY CMa (Hyland *et al.*, 1969) and VX Sgr (Wallerstein, 1971), blue shifted sharp circumstellar absorption components of the zerovolt K I and Ca I lines provide the evidence for mass ejection.

(ii) The rates of mass loss required to support the circumstellar dust shells are entirely reasonable, being of the order of 10^{-5}–10^{-6} $\mathscr{M}_\odot$ yr^{-1} although Davies *et al.* (1972) suggest that mass loss rates of 10^{-3} $\mathscr{M}_\odot$ yr^{-1} are required to maintain the circumstellar material surrounding NML Cyg.

(iii) At least in the case of the long-period variable stars, which are highly evolved, the circumstellar material can in no way be identified with the remnants of a protostellar dust cloud but must be of the star's own fabrication.

(iv) The most telling evidence in favour of the hypothesis comes from the correlation of the separation of the OH velocity peaks ΔV(OH) with the infrared 3.5–10.2 μm colour, which has been independently noted by Hyland, Hirst *et al.* (1972) and Wilson *et al.* (1972). This correlation is shown in Figure 7.

ΔV(OH) can be regarded as a crude estimate of the system's rate of mass ejection, while the 3.5–10.2 μm colour gives a good estimate of the optical depth of circumstellar dust. A further characteristic of this correlation which has not previously been noted is the break in the distribution which occurs around the values ΔV(OH)$\sim$10–14 km s^{-1}. Since this is precisely the range of escape velocity for material in the photospheres

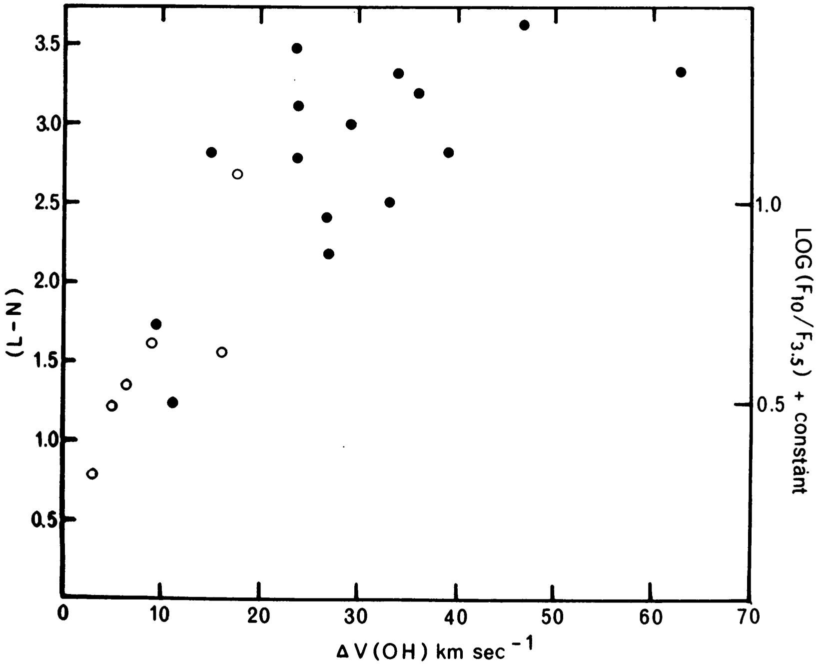

Fig. 7. The correlation of the 10.2 to 3.5 μm flux ratio (or $[L-N]$ colour) with the velocity separation of the OH emission peaks, ΔV(OH), for the 1612 MHz sources (filled circles) and the 1665/1667 MHz emitters (open circles). This correlation is discussed in the text in terms of mass loss and the formation of circumstellar dust shells.

of M giants and supergiants, the figure may be interpreted as showing empirically that if the velocity of ejection is below the escape velocity, thick circumstellar dust shells will not form, but that if the escape velocity is exceeded, then thick circumstellar dust shells almost invariably do form. The fact that the observed position of NML Cyg in this diagram is entirely consistent with the above picture contradicts the protostellar remnant hypothesis.

V. Infrared and Microwave Variability of the OH/IR and H_2O/IR Sources

(a) GENERAL CONSIDERATIONS

One of the most important tasks which has been undertaken regarding the OH/IR and H_2O/IR sources has been to establish the relationship between the infrared and microwave flux densities. Although Hyland *et al.* (1972) showed that such a relationship appeared to exist (see their Figure 9), it was clear that a co-ordinated study of the infrared and microwave variations was necessary to clarify the situation. The recent studies of Schwartz *et al.* (1974) for H_2O sources and Harvey *et al.* (1974) for OH sources fill this need and because of their importance will be discussed in some detail here.

(b) INFRARED VARIABILITY

The studies of variability cover eight H_2O/IR sources (both long-period variable stars and irregular variables) and 14 OH/IR sources (ten 1612 MHz sources and four main-line emitters). They thus give comprehensive results on all the common types of these sources.

The infrared variations are interesting in themselves and have the following characteristics:

(i) All sources investigated with the exception of the supergiants NML Cyg and VY CMa showed variations at 2.2 μm between 0.5 mag and 2.5 mag.

(ii) The infrared phases lag the visual by approximately 0.1–0.2 of a period, and the period is the same as the visual period within the errors of observation, covering the range 300–700 days.

(iii) Colour variations are seen to occur in the sense that the infrared continuum is bluer at maximum light and redder at minimum. Although data on the H_2O sources is available only at a single wavelength (2.2 μm), the colour variations should be similar.

Among the most interesting results are the correlations which are evident between the quantities: the period, the 2.2 μm amplitude, colour and velocity separation of the OH emission peaks, in particular for the long period variable M stars. These are shown in Figure 8. The colour-velocity separation correlation has been discussed in Section IV, the period-velocity separation correlation has been noted by Dickinson and Chaisson (1973), and period-amplitude relations from observations at shorter wavelengths have been discussed in the literature (Merrill, 1960; Lockwood and Wing, 1971).

The causal relationships among the four quantities are unclear and may indeed

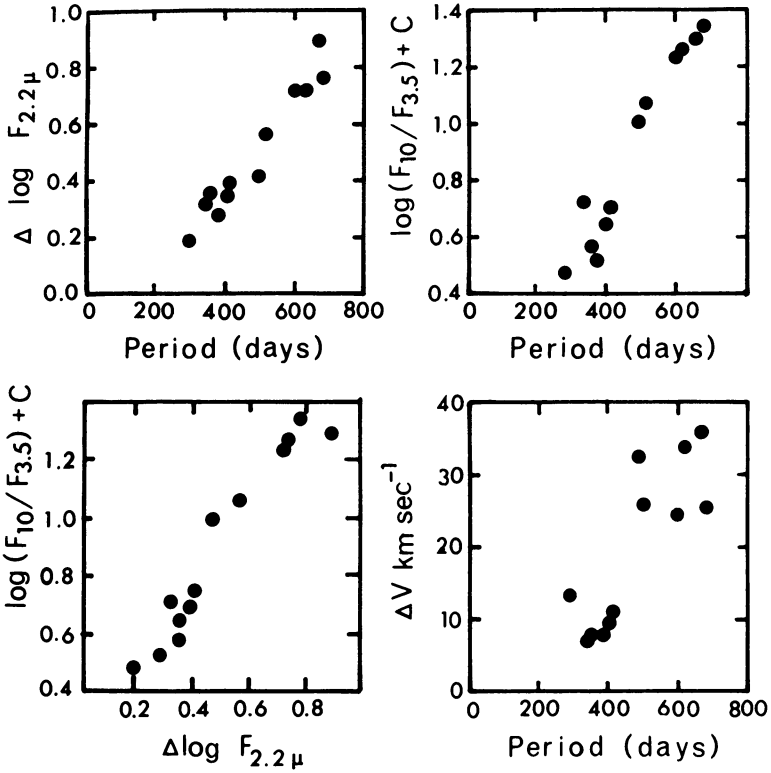

Fig. 8. The observed correlations between the log of the amplitude of variation at 2.2 μm, the 10.2 to 3.5 μm flux ratio, the velocity of separation of the OH emission peaks (ΔV), and the period, for long-period variable OH/IR stars (Harvey *et al.*, 1974).

depend on a further parameter such as luminosity, as one expects a period-luminosity relation to exist for the long period variable stars. Certainly the association of longer periods and larger amplitudes with larger velocity separation and infrared excesses suggests that the mass ejection processes are intimately connected with the mechanical pulsation mechanisms, and that mass outflow due to radiation pressure on dust grains may be a secondary process which dominates only at large distances from the star.

(c) CORRELATIONS OF THE INFRARED AND MICROWAVE VARIABILITY

The empirical relationships which have been defined by the investigations of Schwartz *et al.* (1974) and Harvey *et al.* (1974) are:

(i) The infrared and microwave variations of the long period variable 1612 MHz OH/IR and 1.35 cm H_2O/IR stars are periodic, and have the *same period and phase* within the observational limits. Examples of such variations taken from the above papers are shown in Figure 9.

(ii) The 1665/1667 MHz variations are more random than the 1612 MHz variations and no definite correlation with the infrared variations has been established.

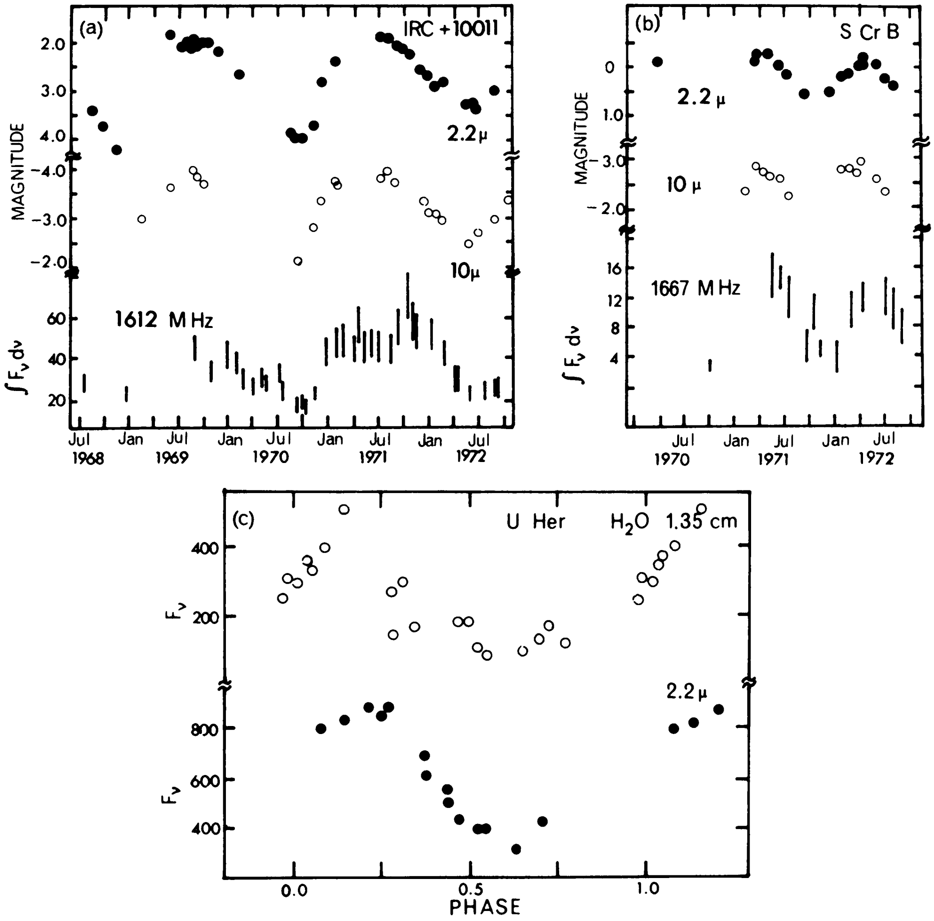

Fig. 9. (a) Observed infrared and 1612 MHz OH variations of the highly variable 1612 MHz source IRC+10011. (b) Observed infrared and 1667 MHz OH variations for the mainline emitter S CrB. (c) Observed infrared and 1.35 cm H_2O variations for the H_2O source U Her.

The observations shown in (a) and (b) are taken from Harvey *et al.* (1974) and those in (c) from Schwartz *et al.* (1974).

(iii) The amplitude of variation in the OH microwave flux is similar or significantly smaller than the amplitude at infrared wavelengths. On the other hand, the amplitude of the 1.35 cm H_2O variations may be larger than the infrared amplitudes.

(iv) The 1612 MHz OH lines and the H_2O lines show no velocity variations within the observational limits of 0.3–0.5 km s^{-1} (which is of course different from observations of spectral lines in the optical).

The interpretation of these observations in terms of the coupling of the microwave emission regions to the other components of simple OH/IR systems as envisaged in Section I places stringent conditions on future models which may be proposed.

(d) RADIATIVE COUPLING OF THE INFRARED AND MICROWAVE EMISSION

The observational results on infrared and microwave variability show that there is strong coupling between the pulsations of the central source and the microwave emission processes. The nature of this coupling has been investigated (Harvey *et al.*, 1974) and *radiative coupling* appears to be the only viable alternative. Mechanical coupling of the regions by mass motions has been rejected on several counts:

(i) VLBI observations show that the microwave emission may come from regions up to 10^{16} cm from the central source;

(ii) the circumstellar densities need to be as low as 10^7 cm^{-3} or quenching of the maser processes by collisions becomes important, and these low densities require the regions also to be several stellar radii from the central source;

(iii) the stability of the velocities of the OH and H_2O lines differs from the variability of line velocities in the stellar photosphere and also indicates that the microwave emission regions are mechanically decoupled from the central source; and (iv) the observed velocities of mass motion (up to ~ 50 km s^{-1}) are such that large phase lags (up to several years) would be required for the mechanical coupling of the stellar pulsations with regions situated between 10^{14} and 10^{16} cm from the central source, in disagreement with observation.

The proposed radiative coupling may be obtained by three separate mechanisms.

(i) The radiation from the central source may affect the equilibrium population density of the OH and H_2O molecules responsible for the microwave emission. This can be discounted not only because the UV radiation field required to dissociate both OH and H_2O molecules is weak in regions surrounding late M stars, but also because such a process would act in the *wrong sense*; i.e., at maximum light the dissociation would be strongest, whereas the microwave emission is seen to increase.

(ii) The variable radiation from the central source may contribute to the collision rate, which determines the extent of population inversion in the masering region. This suggestion is also unlikely since neither the microwave line widths or velocities are observed to vary, as would be expected in the case of large changes in the collision rates. Further reasons are given by Harvey *et al.* (1974).

(iii) The most likely explanation is that of *radiative pumping* of the OH and H_2O molecules by infrared radiation as has been suggested by Shklovskii (1967), Litvak (1969a), and most recently Litvak and Dickinson (1972).

Such a mechanism is consistent with all observations to date. In particular it has been shown to be energetically possible if the infrared pump radiation lies between 2 and 40 μm (Harvey *et al.*, 1974), and indeed pumping by 2.8 μm or 35 μm photons has been suggested for the OH sources. It has also been suggested that H_2O sources are pumped by 2.7 μm radiation (Litvak, 1969b).

It is not the purpose of the review to detail the infrared pumping schemes which have been proposed to explain OH/IR and H_2O/IR sources. Accurate predictions from such models require a more detailed knowledge of the conditions prevailing in the masering regions than currently available, although the schemes proposed by

Litvak and Dickinson (1972) appear to qualitatively reproduce the observed OH characteristics. The degree of saturation of the masers is still a point of debate, although for the OH sources most authors favour the suggestion that the masers are at least partly saturated. There are a number of mechanisms which can account for the different observed infrared and microwave amplitudes. For the H_2O sources the situation is less clear, and Schwartz *et al.* (1974) have shown that either an unsaturated or saturated maser model can be used to explain the variations in R Aql.

VI. Some Other Properties

Although most of the major properties of OH/IR and H_2O/IR sources have been covered in this paper, it has been necessary to omit detailed discussion of a number of interesting characteristics. Two of these should however be briefly mentioned here.

(a) SPATIAL DISTRIBUTION OF OH/IR SOURCES

The spatial distribution of the OH/IR sources has been found to be typical of the long-period variable M stars and M supergiants. However, two interesting differences have been noted between the 1612 MHz and the mainline sources (Wilson *et al.*, 1972). Working on the assumption that the luminosity of all the long-period variable stars is 10^4 $L_\odot$ at maximum light, it is found that the average distance of the mainline sources is roughly one-third of that derived for the 1612 MHz sources. This correlation is also evident in the K magnitudes of the sources, which are on the average much brighter for the mainline sources. If, as suspected, a period-luminosity law exists for long-period variable M stars, one may infer from the period-colour relationship discussed earlier that the mainline emitters have intrinsically lower luminosities than the 1612 MHz sources. If this possibility is included, the differences between the spatial distribution of mainline and 1612 MHz OH/IR sources are enhanced. The probable explanation for this phenomenon is that the intrinsic luminosity of the mainline OH emission is also lower than for the 1612 MHz sources.

(b) THE RATIO (R) OF THE INTEGRATED MICROWAVE OH LUMINOSITY TO THE TOTAL OPTICAL AND INFRARED LUMINOSITY

This quantity bears directly on the question raised above. It is derivable from the observations and is independent of distance. The values obtained for both 1612 MHz and mainline OH/IR sources are plotted in Figure 10 against the 3.5–10.2 μm colour ($L-N$), in the manner of Hyland, Hirst *et al.* (1972). There is an apparent general increase in R as a function of colour (i.e., increasing shell characteristics), though this dependence is largely enhanced by the large values attributed to the supergiant sources. While the M supergiants generally have larger values of R than the long-period variables, for the latter there appears to be an upper limit independent of colour. No explanation has been advanced for this apparent upper limit, but it may be related to the maximum efficiency of infrared pumping and to the fact that in the long-period variables the 2.8 μm OH line lies in a region of heavy photospheric absorption by

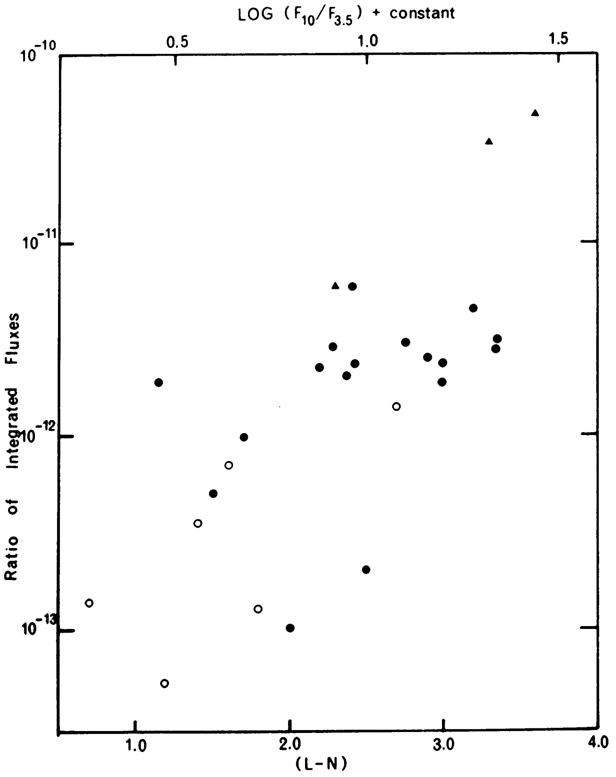

Fig. 10. The ratio (R) of the integrated OH luminosity to the total optical and infrared luminosity as a function of the 10.2 to 3.5 μm flux ratio (or $L-N$ colour). The 1612 MHz supergiant sources are shown as filled triangles, the 1612 MHz long period variable sources as filled circles, and the 1665/1667 MHz long-period variable sources as open circles.

H_2O, which reduces the radiation field by a significant amount. This effect is worthy of further investigation.

The average value of R for the mainline emitters is almost an order of magnitude lower than for the 1612 MHz long-period variable sources (although the maximum values are similar), and this would also help to account for the different observed spatial distributions of the two classes of source.

Finally, Figures 7 and 10 can be used to predict the colour and integrated optical and infrared luminosity from the OH characteristics of the unidentified sources discussed in Section II. Such considerations indicate that bright infrared sources should be found associated with these OH sources, the present lack of which suggests that they may have properties unlike the 'classical' OH/IR stars discussed in this review.

VII. Conclusions

In this paper current knowledge on the infrared properties of the circumstellar OH/IR and H_2O/IR sources has been reviewed in terms of the simple schematic model proposed in the Introduction. This model still appears to be valid as a crude approximation to such systems, and the major characteristics bear repeating here:

(i) The OH/IR and H_2O/IR sources discussed here have a central stellar component consisting of an M supergiant or long-period variable M star. These stars are all oxygen rich and have a limited range of photospheric temperatures such that the partial pressures of OH and H_2O molecules are close to the maximum achievable.

(ii) All the central stars appear to be losing mass, and those with higher rates of mass loss have thicker circumstellar dust shells, a tendency towards the strongest OH emission, and a predominance of 1612 MHz emission.

(iii) The masering regions appear to be at distances up to 10^{16} cm from the central source and are radiatively coupled to the luminosity variations of that source. Radiative pumping in the 2–40 μm region appears to be consistent with all the observations.

Although the basic characteristics of the OH/IR and H_2O/IR sources appear to be well established, many unsolved problems await the investigator. The nature of the new unidentified OH/IR sources, the geometry of the masering and infrared emitting regions, the causal relationships between stellar pulsation and mass loss, and more realistic investigations of the infrared pumping mechanisms still have to be explored. The investigations of OH/IR and H_2O/IR sources discussed in this review have been a prime example of the fruitful cooperation which can be achieved between the optical, infrared, radio and theoretical astronomer, and it is to be hoped that such cooperation will continue in the field and spread to other domains of astronomical research.

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References

Caswell, J. L. and Haynes, R.: 1973, in preparation.
Caswell, J. L., Robinson, B. J., and Dickel, H. R.: 1971, *Astrophys. Letters* **9**, 61.
Davies, R. D., Masheder, M. R. W., and Booth, R. S.: 1972, *Nature Phys. Sci.* **237**, 21.
Dickinson, D. F. and Chaisson, E. J.: 1973, *Astrophys. J. Letters* **181**, L435.
Eliasson, B. and Bartlett, J. F.: 1969, *Astrophys. J. Letters* **155**, L79.
Feast, M. W.: 1963, *Monthly Notices Roy. Astron. Soc.* **125**, 367.
Frogel, J. A.: 1970, *Astrophys. J. Letters* **162**, L5.
Gillett, F. C., Stein, W. A., and Solomon, P. M.: 1970, *Astrophys. J. Letters* **160**, L173.
Glass, I. S. and Feast, M. W.: 1973, *Astrophys. Letters* **13**, 81.
Hardebeck, E. G.: 1972, *Astrophys. J.* **172**, 583.
Hardebeck, E. G. and Wilson, W. J.: 1971, *Astrophys. J. Letters* **169**, L123.
Harvey, P. M., Bechis, K. P., Wilson, W. J., and Ball, J. A.: 1974, *Astrophys. J. Suppl.* **27**, No. 248.
Herbig, G. H.: 1970, *Astrophys. J.* **162**, 557.
Hyland, A. R., Becklin, E. E., Neugebauer, G., and Wallerstein, G.: 1969, *Astrophys. J.* **158**, 619.
Hyland, A. R., Becklin, E. E., Frogel, J. A., and Neugebauer, G.: 1972, *Astron. Astrophys.* **16**, 204.
Hyland, A. R., Hirst, R. A., Robinson, G., and Thomas, J. A.: 1972, *Astrophys. Letters* **11**, 7.

Litvak, M. M.: 1969a, *Astrophys. J.* **156**, 471.
Litvak, M. M.: 1969b, *Science* **165**, 855.
Litvak, M. M. and Dickinson, D. F.: 1972, *Astrophys. Letters* **12**, 113.
Lockwood, G. W. and Wing, R. F.: 1971, *Astrophys. J.* **169**, 63.
Merrill, P. W.: 1960, *Stars and Stellar Systems* **6**, 525.
Neugebauer, G. and Leighton, R. B.: 1969, *Two Micron Sky Survey, A Preliminary Catalog*, NASA, Washington, D.C.
Nguyen-Quang-Rieu, Fillit, R. and Gheudin, M.: 1971, *Astron. Astrophys.* **14**, 154.
Robinson, B. J., Caswell, J. L., and Goss, W. M.: 1970, *Astrophys. Letters* **7**, 79.
Robinson, B. J., Caswell, J. L., and Goss, W. M.: 1971, *Astrophys. Letters* **7**, 163.
Schwartz, P. R. and Barrett, A. H.: 1970, *Astrophys. J. Letters* **159**, L123.
Schwartz, P. R. and Barrett, A. H.: 1971, in G. W. Lockwood and H. M. Dyck (eds.), *Proc. Conference on Late Type Stars*, Kitt Peak National Obs., Tucson, Arizona, p. 57.
Schwartz, P. R., Barrett, A. H., and Harvey, P. M.: 1974, *Astrophys. J.* **197**, 491.
Shklovskii, I. S.: 1967, *Astr. Circ. U.S.S.R.* **424**, 1.
Tsuji, T.: 1964, *Ann. Tokyo Astron. Obs.* **9**, 1.
Turner, B. E.: 1970, *J. Roy. Astron. Soc. Can.* **64**, 221.
Wallerstein, G.: 1971, *Astrophys. Letters* **7**, 199.
Wilson, W. J. and Barrett, A. H.: 1971, in G. W. Lockwood and H. M. Dyck (eds.), *Proc. Conference on Late Type Stars*, Kitt Peak National Obs., Tucson, Arizona, p. 77.
Wilson, W. J. and Barrett, A. H.: 1972, *Astron. Astrophys.* **17**, 385.
Wilson, W. J., Barrett, A. H., and Moran, J. M.: 1970, *Astrophys. J.* **160**, 545.
Wilson, W. J., Schwartz, P. R., Neugebauer, G., Harvey, P. M., and Becklin, E. E.: 1972, *Astrophys. J.* **77**, 523.
Winnberg, A., Goss, W. M., Höglund, B., and Johansson, L. E. B.: 1973, *Astrophys. Letters* **13**, 125.

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DISCUSSION

Davies: You suggested that the OH and H_2O molecules seen in the radio masers were injected from the central star. I think there is good evidence, at least for the M supergiant OH/IR objects, that the OH and H_2O are associated with the pre-existing circumstellar cloud for the following reasons:

(i) The angular momentum derived from the radio interferometry is far too large for gas ejected from a star.

(ii) The amount of gas ($\sim 10^{-1}\ M_\odot$) and rate of mass outflow ($10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$) are greater than for any known group of stars.

(iii) There is already evidence in VY CMa of a large gas and dust complex surrounding the IR/OH object.

Hyland: Firstly, the observations of the long period variable OH/IR stars provide circumstantial evidence for the expulsion of the emitting OH and H_2O molecules from their own atmospheres which is hard to ignore. Further, infrared objects whose central stellar sources have high temperatures (such that OH and H_2O molecules cannot form in their atmospheres) do not appear to exhibit OH or H_2O microwave emission, regardless of whether the circumstellar material appears to be due to mass loss (such as for RV Tauri stars) or is the possible remnant of a protostellar cloud (as may be the case for Z CMa). It is true that the angular momentum of the circumstellar material surrounding NML Cyg and VY CMa appears to be embarrasingly high. However, it is marginally possible from the numbers currently available to explain such high angular momentum if those stars were rotating near break-up velocity while on the main sequence. The high rate of mass outflow does not appear to be too much of a problem given the erratic and energetic nature of the outbursts in VY CMa.

Donn: What is the wavelength band of your infrared search?

Hyland: The effective wavelength of the television system and infrared filter is 8000 Å and corresponds closely with the Kron I system.