THE STRUCTURE OF FOUR 1612 MHz OH EMISSION SOURCES

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SUMMARY

Three M-type supergiant infra-red/OH objects, NML Cyg, VY CMa and VX Sag, and the W43A source have been studied with the Mark II–Mark III interferometer in the 1612 MHz OH satellite line. Detailed structure has been determined for the NML Cyg and VY CMa sources. The blue-shifted emission was found at the centre of the objects while the zero velocity emission (relative to the star) was found at the periphery. Both objects were elongated in a direction perpendicular to their apparent rotation axis. A model of these objects has been constructed from the observations which indicates an efflux of $5 \times 10^{-3}$ solar masses per year from the vicinity of the central star. The implications of the results for theories of circumstellar clouds is discussed.

I. INTRODUCTION

The OH maser sources discovered at 18-cm wavelength are objects of small angular size which require interferometers of at least 10-km baseline to separate their components. The individual components can only be resolved with baselines of 100 km or more (see for example Moran et al. 1968; Cooper, Davies & Booth 1971). Interferometer observations can give precise information about the relative positions of the velocity components within an OH source—in the stronger circum-polar sources relative positions can be determined to an accuracy of better than 0.01 arc.

OH masering sources can be classified into several groups according to their characteristic frequency of emission and the associated objects. The most common are the strong 1665 and 1667 MHz emitters associated with compact H II regions (class I sources). The group of OH objects whose structure is investigated in the present work consists of those in which the 1612 MHz satellite line is dominant (class IIb). These are characteristically associated with IR objects which may be M supergiants, Mira variables or extended IR nebulosities. Another property of these OH/IR sources is the grouping of the components into two distinct velocity ranges separated by 20–40 km s$^{-1}$.

Optical studies of the Mira variable and M supergiant stars associated with the OH/IR objects show the presence of absorption features in the atmosphere of the star and in addition emission and absorption features from gas moving towards the observer at a velocity of 20–40 km s$^{-1}$ relative to the star. The stellar velocity is found to be the same as the red-shifted part of the OH spectrum and the outflowing gas has the velocity of the blue-shifted OH spectrum. The M supergiants...
show optical and OH velocities which indicate an expansion of \( \sim 40 \text{ km} \text{s}^{-1} \) whereas the Mira variables show about half this expansion velocity.

The four brightest 1612 MHz OH sources with the characteristic double velocity structure were chosen for the present study. Three (NML Cyg, VY CMa and VX Sag) are associated with M supergiants, and one (W43A) is associated with an H II region in which no IR source has so far been reported. Their positions and distances are given in Table I.

<table>
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<th>Name</th>
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<th>Association</th>
<th>l</th>
<th>b</th>
<th>Distance (pc)</th>
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<td>M3e</td>
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<tr>
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<td>-22 14.2</td>
<td>M4e</td>
<td>8.3</td>
<td>-1.0</td>
<td>1700</td>
<td>-30</td>
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<tr>
<td>W43A</td>
<td>18 45 03</td>
<td>-01 48.3</td>
<td>--</td>
<td>30.9</td>
<td>+0.1</td>
<td>2000</td>
<td>+3</td>
</tr>
<tr>
<td>NML Cyg</td>
<td>20 44 34</td>
<td>39 55.9</td>
<td>M6</td>
<td>80.8</td>
<td>-1.9</td>
<td>500</td>
<td>-17</td>
</tr>
</tbody>
</table>

The salient optical and infra-red properties of these objects will now be summarized. NML Cyg is one of the brightest IR sources and one of the reddest found in the CalTech 2.2 \( \mu \) Survey (Neugebauer & Leighton 1969). Its optical counterpart is an M6 supergiant with more than 13 mag of visual absorption. The circumstellar dust cloud which is believed to produce the IR radiation is at a temperature ranging from 1500 to 250 K on progressing outwards from the star (Stein et al. 1969). Herbig (private communication) does not find any near-infra-red nebulosity greater than 0.5 arc in diameter. If the distance of NML Cyg is taken as 500 pc (Hyland et al. 1969) its luminosity is \( 5 \times 10^4 \) solar luminosities. Limited interferometer observations in the 1612 MHz OH line by Wilson et al. (1970) showed structure within a region 2 arc in diameter.

VY CMa is an M3e supergiant, an irregular variable, imbedded in a nebulosity approximately 8' x 12' arc in p.a. = 290° that has changed its structure at various times in the last 50 yr (Herbig 1972). Within the nebula are a number of condensations each a few arc in diameter. The optical emission from the nebula is plane polarized with the \( E \) vector perpendicular to a radius vector which can be explained in terms of scattering of the light from the central star by circumstellar dust. VY CMa also has strong emission excess in the infra-red which is believed to come from a circumstellar dust cloud which reradiates the light from the central star. Herbig (1970a) argues for a distance of 1.5 kpc based upon its apparent association with the star cluster NGC 2362 where its luminosity would be \( 5 \times 10^5 \) solar luminosities.

VX Sag is an M supergiant in the Carina arm (Humphreys, Strecke & Ney 1972) surrounded by a circumstellar cloud. Its distance is 1.7 kpc, appropriate to its supposed membership of the Sag OB1 association where its luminosity would be \( 4 \times 10^8 \) \( L_\odot \). VX Sag is an M4e SR1 variable with a period of 732 days and is also subject to sudden variations and spectrum changes (Humphreys & Lockwood 1972). VX Sag also shows spectroscopic evidence for an expanding gas shell as well as excess IR emission characteristic of a circumstellar dust cloud (Wallerstein 1971b; Humphreys et al. 1972).

W43 is a thermal radio source with several OH components. The component W43A is classified as an OH/IR source because of the double structure in its
1612 MHz spectrum, even though no IR source of the Neugebauer & Leighton catalogue is known at its position (Robinson, Goss & Manchester 1970; Wilson & Barrett 1972). The W 43A OH emission is not at the velocity of the principal H II region features at 90–100 km s\(^{-1}\) and is therefore probably not associated with the main H II region. If the velocity of the red-shifted 1612 MHz feature at 40±5 km s\(^{-1}\) is taken as the true systemic velocity the distance is 2900 pc (Robinson et al. 1970). Because of the uncertainty in assigning a distance for W 43A we will adopt a value of 2000 pc which corresponds to the Sagittarius arm.

2. THE OBSERVATIONAL AND REDUCTION TECHNIQUES

2.1 The interferometer

The present observations were made with the Mark II–Mark III interferometer during 1971 March and April. At the OH satellite line frequency of 1612-231 MHz the baseline length of 24 km corresponds to \(1\times10^5\) wavelengths and produces a fringe separation of \(1^\circ6\) arc in the sky.

Signals at each telescope were received through a scalar feed and polarimeter system which could be set to accept either LH or RH circular polarization. This was followed in each case by a parametric amplifier receiver which produced an overall system noise of 150–200 K. Local oscillator coherence at the two ends of the interferometer was produced by phase-locking the local oscillator at one station with a signal derived from the other station which was transmitted over a radio link. The intermediate frequency band containing the OH signal from the outstation was likewise brought back to the home-station over a radio link.

The 256-channel digital spectrometer was used in the cross-correlation mode to obtain the complex (sine and cosine) spectrum at any instant. The natural fringe rate was slowed by analogue means to a rate of less than 0.1 fringe per minute. At this rate it was possible to take one complex spectrum per minute and not lose precision in determining the relative phases of the channels.

Observations of the sources VY CMa and NML Cyg were repeated with a range of IF bandwidths to obtain the relative positions of all the components and at the same time to resolve fully all the components in frequency.

2.2 Reduction technique

The sine and cosine outputs from the cross-correlator were converted to an amplitude and phase for each of the 128 frequency channels. Although the interferometer was not sufficiently phase-stable in the long term to determine precise positions, it was possible to obtain the relative positions of components in the spectrum by choosing one channel as a reference. The relative phase variation \(\Delta\phi\) with hour angle between two components with a separation of \(\Delta D\) in declination and \(\Delta H\) in hour angle (HA) is given by

\[
\Delta\phi = 2\pi L \sin d \cos D \Delta D - 2\pi L \cos d \sin D \cos (H - h) \Delta D - 2\pi L \cos d \cos D \sin (H - h) \Delta H, \quad (1)
\]

where \(L\) is the interferometer baseline in wavelengths, \(d\) and \(h\) are the declination and HA of the baseline (−19° 17′ and 04h 05m 32s−5), and \(D\) and \(H\) refer to the source. For two point-source components the above relation can be solved directly to obtain \(\Delta D\) and \(\Delta H\) from the variation of \(\Delta\phi\) with \(H\). This processing was done in the Manchester and Chilton Atlas computers.
Fig. 1. $U-V$ plane tracks as seen from the source when looking at the interferometer for the sources NML Cyg, VY CMa, W43 A and VX Sag.

Because of the different declinations of the four sources they are observed with different baseline resolutions. The projected baselines of the interferometer as seen from the sources, called the $U-V$ plane track, are shown in Fig. 1. Clearly NML Cyg, which is circumpolar at Jodrell Bank, will give the best relative positions for the components. The other sources which are at low declinations will be mapped with less precision.

Some of the components in the spectra of the sources studied in this investigation overlap in frequency even when adequate frequency resolution is used. Consequently the relative amplitude and phase plots required further inspection and analysis to determine the positions of the various components present. Fig. 2 shows examples of $A$ and $\phi$ plots with varying amounts of contamination from adjacent components. This contamination is intrinsic to the emitted source spectrum and cannot be removed by using higher frequency resolution.

The positions of individual components can be derived by fitting the observed phase plot to equation (1) in cases where a component is relatively free from contamination. For most components the contamination is by a single component adjacent in frequency and it is possible to fit a double point-source model. Checks can be made on such models by making the fit over several channels in the complex so as to include different relative amounts of the two components.

3. RESULTS FOR INDIVIDUAL SOURCES

3.1 NML Cygni

Since NML Cyg has only a small (<5 per cent) circular polarization at 1612 MHz and since all the components on one polarization are visible on the other, observations were limited to one polarization (RH). The overall 1612 MHz
spectrum of NML Cyn is shown in Fig. 3 along with all the spectral information available for this source, including the main OH lines, H₂O emission and optical emission and absorption features. The optical absorption features which are believed to represent the velocity of the central star are at the red-shifted end of the 1612 MHz OH emission spectrum.
Fig. 3. The spectrum of NML Cyg. The 1612, 1665 and 1667 MHz lines of OH, the
1.3 cm water vapour spectrum (Schwartz & Barrett 1970) and the optical absorption
(stellar) velocity are shown. Add \(-16.5\) km s\(^{-1}\) to obtain velocities relative to the Sun.

In order to cover the whole velocity range in the NML Cyg 1612 MHz
emission with adequate frequency resolution, observations were made in five
separate bandwidths. Amplitude and phase plots covering 24 h in HA were
obtained for \(\approx 400\) channels in all.

From this large quantity of information some 63 independent emitting features
were identified. These features were recognized either by their being at a separate
position and/or being a distinct velocity feature in the spectra. Their relative
positions are plotted in Fig. 4; the reference component chosen for this OH
source was the \(-23.9\) km s\(^{-1}\) component. The errors in the 10 best determined
positions are \(\approx\)0.005 arc. In the weaker components of the spectrum the un-
certainty in position is \(\approx\)0.010 arc.

An interesting systematic picture emerges from the map of component positions
in Fig. 4. The components lie in a region 3.3 \(\times\) 2.3 arc in extent with its major
axis at a position angle of 150°. The red-shifted components (+6 to +23 km s\(^{-1}\))
are found around the outer periphery of the object and are concentrated at the two
ends of the major axis. The blue-shifted components (-29 to 2 km s\(^{-1}\)) fill the
inner regions of the object and all lie inside the distribution of red-shifted com-
ponents. All the strongest red-shifted and blue-shifted components are found in
the NW half of the source. A further systematic trend can be seen in the red-shifted
component velocities. The velocity falls continuously from the NW to the SE end
of the object. This is interpreted below as the result of rotation about the minor
axis of the object. The inner blue-shifted emission is the gas expanding radially outwards towards the observer from the central M supergiant.

We will now describe some of the detail which may be found in maps made with the highest frequency resolution. Adjacent points (separated by 0.305 kHz = 0.057 km s\(^{-1}\)) in a section of a 39 kHz overall bandwidth observation of the bright components around \(-23\) km s\(^{-1}\) are shown in Fig. 5. The positions have all been obtained by fitting a sine wave of 24 h (HA) period to the observed phase plot. Rms errors on each point are typically in the range \(\pm 0.004\) to \(\pm 0.008\) arc. It can be seen that the derived positions at adjacent velocities vary continuously in position. The components are broader in velocity than the channel separation of 0.05 km s\(^{-1}\). This suggests that the emission comes from regions which are extended compared with the incremental changes in position. Otherwise, if the components were of small angular diameter, the derived positions for the channels having a major response on a particular localized velocity component would all show the same position within the errors of measurement. A channel situated at a
velocity intermediate between two components will give the position corresponding to the strongest contributing component, using our fitting programme. The observed channel-to-channel change in position is interpreted as the movement of the centroid of the emitting volume with velocity. This movement is quite small. For example the feature at $v = -26.35$ km s$^{-1}$ is distributed over a velocity range of $0.46$ km s$^{-1}$ and a spatial extent of $0''.045$ arc. Similarly the feature at $-25.40$ km s$^{-1}$ extends $0''.026$ arc over a velocity range of $0.50$ km s$^{-1}$.

The size of the individual emitting regions can be estimated in two ways. First the variation of fringe visibility with baseline provides an estimate of the diameter, or at least an upper limit, for each component. Such a calculation is slightly complicated in the case of NML Cyg because many of the channels even at the highest velocity resolution contain more than one positional component. The examination of a sample of the channels over the whole velocity range covered by NML Cyg gave no evidence for any spatial resolution of the components. The fringe visibility of all these components fell by less than 10 per cent between minimum and maxi-
mum projected baselines. This implies that the components have a half-power diameter of less than 0''3 arc. A second method of determining the diameter of features is available from position plots of closely spaced channels such as Fig. 5. The change of position with velocity in a feature gives an estimate of its size. Typical sizes found in this way are 0''03 to 0''10 arc for the brighter features in NML Cygni. Strictly these are lower limits to the size because the emission within a channel may come from an extended area and we have only measured the spread in position of the centroid in each velocity channel. In what follows we will take 0''05 arc as the typical size of an emitting feature.

The above estimates of the angular size of the components may be compared with that given by Wilson et al. (1970) who state that the characteristic component size is 0''08 arc. They could not be sure of this result because of the severe undersampling in HA and because of the presence of overlapping velocity components. The present results show that the situation is indeed complex and that it is necessary to make continuous observations in HA to obtain the relative positions of the components and their sizes. A method of demonstrating the existence of overlapping, spatially separated components is demonstrated in Fig. 6, where the spectrum

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**Fig. 6. Spectra (total power) of NML Cyg obtained with a single telescope compared with vector averaged spectra obtained with the Mk II-Mk III interferometer. (a) The blue-shifted end of the spectrum; the reference channel is at $-23.9$ km s$^{-1}$ for the interferometry. (b) The red-shifted end of the spectrum; the reference channel is at $+19.6$ km s$^{-1}$ for the interferometry.**

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taken with a single telescope is compared with the mean vector amplitude of the interferometer spectra using a channel set on one of the 'clean' components as a phase reference. If all the components were fully separated in frequency then the interferometer spectrum would be the same as the single dish spectrum. However,
where there is overlapping in frequency and the components are separated in position, the amplitude of the interferometer spectrum is less than the single dish spectrum because the mean interferometer amplitude is derived from the sum of two vectors with varying phases.

Using the above estimates of the angular diameter of the individual emitting regions in NML Cyg, it is possible to calculate their brightness temperatures. For the brighter components in the spectrum near \(-20\ \text{km s}^{-1}\) the brightness temperature is in the range \(1-5 \times 10^{10}\ \text{K}\). The implication of this result will be discussed in Section 4.

3.2 VY CMa

The 1612 MHz spectrum of VY CMa is shown in Fig. 7 with the main line

![Spectrum of VY CMa](https://example.com/spectrum)

**Fig. 7.** The spectrum of VY CMa. The 1612, 1665 and 1667 MHz spectra of OH, the 1.3 cm spectrum of H$_2$O (Sullivan 1971) and the main optical lines (Wallerstein 1971b) are shown. Add \(+19.0\ \text{km s}^{-1}\) to obtain velocities relative to the Sun. Optical emission features are labelled E and absorption is labelled A. The 1665 MHz OH emission near \(45\ \text{km s}^{-1}\) was observed by Sullivan (1971).
OH, the H$_2$O and the optical spectral features. Because of its low declination VY CMa could be tracked for only 6 h. As a consequence less accurate relative positions were obtained as compared with NML Cyg. Nevertheless an attempt was made to obtain the relative positions of all components by using a full range of spectrometer bandwidths so as to resolve the spectrum fully.

A formal solution of the observed phase variation to obtain the relative position offsets was made for each channel where emission was detected. This procedure will give true positions for components clearly separated in velocity, but could give uncertain positions if the components are overlapping in velocity and displaced spatially because of the restricted HA coverage. However, such confusion effects will also be shown up in the amplitude information. As mentioned above, the vector amplitude averaged over the period of observation will provide a good indication of confusing effects. This spectrum and the single telescope spectrum are shown for the two ends of the velocity range of VY CMa in Fig. 8(a) and (b). Clearly there are separated components and caution will be necessary in accepting all the derived positions.

![Graphs showing OH emission sources](https://academic.oup.com/mnras/article-abstract/166/3/561/2604763)

**Fig. 8.** Spectra (total power) of VY CMa obtained with a single telescope compared with vector averaged spectra obtained with the Mk II–Mk III interferometer. (a) The blue-shifted end of the spectrum; the reference channel is $-10.3$ km s$^{-1}$ for the interferometry. (b) The red-shifted end of the spectrum; the reference channel is $+47.8$ km s$^{-1}$ for the interferometry.

Fig. 9(a) is the map of all the components which were not too strongly affected by amplitude variations. Positions are plotted relative to the $+47.6$ km s$^{-1}$ component. Some uncertain positions may still be included since in the HA coverage available not all overlapping components will be identified. The errors in the best determined relative positions are $0''15$ arc (2 S.D.) and in the least accurate $0''3$ arc. Despite the large errors in individual relative positions the structure of
Fig. 9(a). *A map of the relative positions of the strongest features in the 1612 MHz source associated with VY CMa. Positions are given relative to the +47.6 km s\(^{-1}\) component. The intensity of the components is indicated qualitatively by the size of the circles. Filled circles represent the blue-shifted end of the spectrum, open circles the red-shifted end. The uncertainty in relative positions of the stronger components is 0\(\cdot\)05 arc along p.a. = 60\(^\circ\) and 0\(\cdot\)25 arc along p.a. = 150\(^\circ\). The errors are approximately twice these values for the weaker components.*

VY CMa is seen to resemble that of NML Cyg with the blue-shifted components confined to an area which lies within the majority of the red-shifted components. Such a systematic arrangement suggests that the positions determined for VY CMa are not severely affected by the limited HA coverage. There is some overlapping of blue- and red-shifted components in the central region of the source. Some of this overlapping could be due to the uncertainty in positions. It should also be pointed out that the HA coverage shown for VY CMa in Fig. 1 implies that the uncertainty in position is mainly along p.a. = 150\(^\circ\). The error in this direction is ~0\(\cdot\)25 arc for the stronger components and ~0\(\cdot\)5 arc for the weaker components plotted. In the orthogonal direction the errors are ~0\(\cdot\)2 of these values.

The overall extent of VY CMa is 2\(\cdot\)2 x 1\(\cdot\)4 arc with its major axis at p.a. = 158\(^\circ\). Examination of the detailed distribution shows a systematic displacement of the
red-shifted components to the SW along the minor axis by $\sim 0''\cdot 3$ arc. This displacement will be discussed in terms of the proposed model of these OH/IR regions in Section 4.

It is of particular interest to compare the shape of the 1612 MHz OH object with the visible nebulosity given by Herbig (1972). This is shown in Fig. 9(b). The centroid of the OH object is assumed to be that of the star since the position of the OH object is known to an accuracy of only $\sim 5''$ arc (Hardebeck 1972). The outline of the OH masering source would then include the optical component B but not components C, D, E or F. Clearly the extended optical nebulosity lies outside the OH object which is presumably the high density kernel of the circumstellar envelope.

The extent of the main line OH sources associated with VY CMa is $\lesssim 0''\cdot 2$ for both the 1665 and 1667 MHz sources (Harvey et al. 1974, in preparation). They are significantly smaller than the 1612 MHz source. No accurate positions are available which allow the main line sources to be located within the 1612-MHz source.

3.3 VX Sag

The 1612 MHz spectrum of VX Sag is shown in Fig. 10 along with the main OH line, H$_2$O and optical spectral features. Since this source is relatively weak and since it can be tracked for only 8 h of HA component positions can be determined with only modest accuracy.

The component separations were found to be much less than in VY CMa. The most accurate relative positions were obtained along the line at p.a. $= 59^\circ$, which is perpendicular to the UV-plane track shown in Fig. 1. Separations relative to the $+17\cdot 2$ km s$^{-1}$ component are plotted in Fig. 11; the blue- and red-shifted
components are shown separately. Position errors are $\pm 0''05$ to $\pm 0''10$ arc along a line at p.a. = 59° and about five times this in the perpendicular direction.

Fig. 11 shows that VX Sag has an extent in p.a. = 59° of no more than $0''4$ arc; indeed some of this spread will be contributed by the measurement errors. The source diameter in this direction could be as small as $0''2$ arc. No extension significantly greater than the errors ($\pm 0''25$ to $\pm 0''50$ arc) was detected along p.a. = 149°.

3.4 W43A

The 1612 MHz spectrum of W43A is shown in Fig. 12 with its main-line OH spectrum. No H$_2$O, optical or infra-red source has been identified with the OH object. The overall shape of the 1612 MHz spectrum is similar to that of the other M supergiant sources described above. There are differences in detail between W43A and the three OH sources identified with M supergiants NML Cyg, VY CMa and VX Sag. For example, W43A has only 30 per cent of the total velocity spread and 25 per cent of the spread at each end of the spectrum; in these respects W43A resembles the Mira variables more than the M supergiants.
**Fig. 11.** A histogram of the relative separation of the 1612 MHz components of VX Sag along a line at p.a. = 59°. Blue-shifted and red-shifted components are shown separately. The typical uncertainty in position relative to the +17·2 km s⁻¹ component is ±0°·06 arc along p.a. = 59°; the uncertainty is ~5 times this value in the perpendicular direction because of the limited coverage in HA possible in the interferometry of this source.

**Fig. 12.** The OH spectrum of W43A at 1612, 1665 and 1667 MHz. There is no optical counterpart to this OH source. Add -16·7 km s⁻¹ to obtain velocities relative to the Sun.
A map of the six RH components of sufficient intensity to be detected in the present observations is shown in Fig. 13. Because of the small north-south range in the UV track the precision in the relative positions of the components is largely in the RA direction (actually along p.a. = 87°); the errors are a factor of 20 times worse in declination. The positions of the components fall into two groups separated by 0.17 arc along p.a. = 87°. One group is associated with the 27.5 km s\(^{-1}\) end of the spectrum and the other with the 40.5 km s\(^{-1}\) end. There is no significant separation of the components within each group and moreover there is no overlap in position between the two groups.

![Diagram](https://example.com/diagram.png)

**Fig. 13.** A map of the positions of the main features of W43A relative to the 40.6 km s\(^{-1}\) component. Because of the limited HA coverage of this source the most accurate relative positions are along p.a. = 87°. Note the factor of 10 difference in scale between RA and Dec.

If the east-west dimensions of W43A are representative of those at other position angles we may conclude that its overall dimensions are \(\sim 0.3\) arc including the spread within each grouping. However, it is possible that the N–S dimension is larger than this. For example VY CMa shows a mean separation of the high and low velocity components along its minor axis direction of 0.4 arc (compared with 0.17 arc for W43A) where its overall extent is 2.2 × 1.4 arc. However, in W43A the overall minor axis extent is only \(\sim 0.3\) which suggests that its angular size is \(\sim 0.2\) of that of VY CMa or NML Cyg. Apart from its smaller angular size we conclude that W43A shows two basic differences from NML Cyg and VY CMa. First its velocity spread is significantly smaller, and secondly there is a complete separation in position between the high and low velocity components which is not found in the identified M supergiants.
4.1 The size of the objects

Information is available for the size of the sources in different wavelength ranges each referring to different regimes within the source. Beginning at the centre of the source we know that the central star (an M3 to M6 for those sources associated with an M supergiant) has a diameter of $4 \times 10^{14}$ cm (Herbig 1970b). Surrounding the star lies the circumstellar dust (and gas) cloud which is responsible for the IR emission. On certain assumptions about the distribution of the dust, estimates can be made of the diameter. For VY CMa and NML Cyg Hyland et al. (1972) give an IR diameter of $3 \times 10^{15}$ cm; for VY CMa Herbig (1970b) proposes a shell with an inner diameter of $\approx 2 \times 10^{15}$ cm and an outer diameter of $\approx 2 \times 10^{16}$ cm. So far no direct measure of the diameter of the IR sources has yet been made. On the other hand, at optical wavelengths there is a long history of observations of VY CMa showing that it may contain five concentrations of reflection nebulosity (Herbig 1972). Its overall extent is 12" by 8" arc (2.8 by 1.9 × 10^{17} cm) which is $\approx 5$ times the OH dimensions. Herbig (private communication) has searched for a similar nebulosity around NML Cyg at $\approx 8000$ Å but found no evidence for any nebulosity with a diameter greater than 5" arc ($\approx 3.9 \times 10^{15}$ cm). In the description of the M supergiant objects which we shall give in Section 4.2 and 4.3 below, the VY CMa type optical nebulosity appears as the outer extension of the gas and dust cloud which is responsible for the OH maser emission. Such a nebulosity may not be seen around NML Cyg because of the heavier dust absorption (possibly as high as 13") in this object.

4.2 Source parameters derived from the observations

4.2.1 The expansion velocity. The M supergiants show two line systems—one associated with the atmosphere of the star itself and the other with gas expanding away from the star. The most red-shifted complex in the 1612 MHz OH spectrum agrees in velocity with the stellar velocity as may be seen in Figs 3, 7 and 10 and Table II. A similar coincidence between the stellar velocity and the red-shifted OH component is found in Mira variables and other OH/IR objects (Wilson et al. 1972; Wilson & Barrett 1972). This suggests that the coincidence in velocity seen

<table>
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<th>Source</th>
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<th>Linear dimensions (units of 10^{16} cm)</th>
<th>Adopted distance (pc)</th>
<th>Velocity of star (km s^{-1} rel. to lsr)</th>
<th>Velocity red-shifted OH (km s^{-1} rel. to lsr)</th>
<th>Velocity of expansion (km s^{-1})</th>
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<tr>
<td>VY CMa</td>
<td>$2.2 \times 1.4$</td>
<td>$4.9 \times 3.1$</td>
<td>1500</td>
<td>50</td>
<td>45 (55)*</td>
<td>56 (66)*</td>
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<tr>
<td>VX Sag</td>
<td>$\lesssim 0.3$ (p.a. = 59°)</td>
<td>$\lesssim 0.8$</td>
<td>1700</td>
<td>24</td>
<td>23 (27)</td>
<td>36 (42)</td>
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<tr>
<td>W43A</td>
<td>$\sim 0.3$ (p.a. = 87°)</td>
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<td>2000</td>
<td>—</td>
<td>40 (41)</td>
<td>13 (14)</td>
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<td>NML Cyg</td>
<td>$3.3 \times 2.3$</td>
<td>$2.5 \times 1.7$</td>
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<td>23</td>
<td>21 (23)</td>
<td>30 (48)</td>
</tr>
</tbody>
</table>

* The velocity of the half-intensity point on the red-shift edge of the spectrum.
† The velocity difference between the half-intensity points at each end of the spectrum.
for a variety of objects is real and is not a model-dependent chance agreement between the velocity of expanding gas on the far side of the star and the doppler-shifted velocity of the starlight reflected in a part of the dust also on the far side of the star (Herbig 1970a). We will proceed on the assumption that the red-shifted OH velocity and the absorption line optical velocity represent the true systemic velocity of the star and the associated gas and dust cloud. The spatial distribution of the OH emission features also supports such an interpretation (see Section 4.3).

Values for the OH expansion velocity of the four objects studied are given in Table II. Two values are given, one is the velocity separation of the centroid of the two complexes of the 1612 MHz OH spectrum and the other is the separation between the outer half-power edges of the spectrum. The three sources identified with M supergiants have expansion velocities in the range 40–60 km s$^{-1}$, while W43A has an expansion velocity of 14 km s$^{-1}$. As mentioned previously we prefer to consider W43A separately from the M supergiants.

4.2.2 Absence of true red-shifted gas. An important negative observation in all the data is the lack of any emission at a velocity red-shifted relative to the star. Such emission at +40 to +60 km s$^{-1}$ relative to the star in NML Cyg or VY CMa is less than 1 per cent of the blue-shifted 1612 MHz emission. Spatially it would be expected in a region on the far side of the star in a region with similar dimensions to that occupied by the blue-shifted gas. The absence of this emission has to be explained in any complete model of the OH/IR sources.

4.2.3 Rotation of the OH/IR sources. In both NML Cyg and VY CMa, the two OH/IR sources which have been adequately resolved in the present investigation, there is clear evidence for rotation in the components of the red-shifted end of the spectrum. The velocity difference is a maximum at the two ends of the major axis and corresponds to a peripheral rotation velocity of $\sim 5$ km s$^{-1}$. The rotation appears to be associated with the elongation of the object in such a sense that the object is a flattened rotating disc.

The rotation is not so clearly evident in the blue-shifted end of the spectrum. There are two factors which may account for this. First, the blue-shifted emission is concentrated near the centre of the object where the line of sight component of the rotational velocity is smaller. Secondly, any spread in expansion velocities is seen to the full in the direction of the centre of the source at blue-shifted velocities, whereas it is a minimum at the edge of the source where the expansion is perpendicular to the line of sight.

Taking the peripheral rotation velocity as 5 km s$^{-1}$ and the major axis diameters given in Table II, the rotation period of NML Cyg is $5 \times 10^3$ yr and of VY CMa is $1.0 \times 10^4$ yr. This rotation time is long compared with the time of $\sim 10^2$ yr that takes gas to move from the vicinity of the star to the outer periphery of the OH object at the expansion velocities given in Table II.

4.2.4 Gas density in the masering column. Some indication of the gas density in the masering regions of the OH/IR sources can be derived from the observations. It will be assumed that the maser action is occurring in a column through an appreciable depth of the source where the molecules are at similar velocities. Individual components are considered to result from pumped molecules in particular lines of sight which have an excess at certain line-of-sight velocities. Such differences in column density of pumped molecules may be only $\sim 10$–20 per cent but these can lead to 10–20 per cent differences in the exponent which produce factors of $e^{2-4}$ in maser intensity where the maser gain is $\sim e^{20}$. We therefore will assume
that the derived densities refer to a relatively uniform gas cloud surrounding the M supergiant.

A detailed theory which predicts many of the observed properties of the class IIb OH sources is the IR pumping theory of interstellar OH (Litvak 1969 and Litvak & Dickinson 1972). Whilst this is by no means the only possible approach we will adopt the Litvak model. This indicates that there is a limited range of gas densities under which IR pumping can produce strong maser action at 1612 MHz and, in order that there is sufficient optical depth to the IR field,

$$\int n_{\text{OH}} \cdot \frac{\nu}{\Delta \nu} \cdot dl \sim 10^{23} \text{ cm}^{-2}$$

where $\Delta \nu/\nu$ is the fractional width of the line. From the spectra and Fig. 5, we find that the width of the typical component is $\sim 0.5 \text{ km s}^{-1}$ so that $\nu/\Delta \nu = 6 \times 10^5$ and

$$\int n_{\text{OH}} \cdot dl \sim 1.7 \times 10^{17} \text{ cm}^{-2}.$$  

We will take a value of $n_{\text{OH}}/n_{\text{H}} \simeq 10^{-5}$ which corresponds to the condition that 10 per cent of all oxygen atoms are in the form of OH; this value is in the middle of the range found for interstellar clouds (Davies & Matthews 1972). The hydrogen integral in the masering column is then

$$\int n_{\text{H}} \cdot dl = 1.7 \times 10^{22} \text{ cm}^{-2}.$$  

Taking a masering depth of about half the cloud radius, viz. $\sim 5 \times 10^{15} \text{ cm}$ (see Section 4.3), we obtain $n_{\text{H}} \sim 3 \times 10^{6} \text{ cm}^{-3}$. This will be adopted as the density in any masering column in objects such as VY CMa and NML Cyg. This refers to regions near the circumference of the objects, i.e. at 1.2 to 2.4 $\times 10^{16} \text{ cm}$ from the centre of NML Cyg and VY CMa.

Further information is available from the observations which confirm the above estimates of the OH density. The equivalent brightness temperature of the more intense components is $\sim 4 \times 10^{10} \text{ K}$ based on a component flux of $200 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ and a component diameter of $0'' \cdot 05 \text{ arc}$. If the temperature of the gas is $\sim 400 \text{ K}$, the temperature in the outer regions of the IR source, the maser gain is $10^8 = e^{18.4}$. The corresponding line narrowing is $\sqrt{18.4} \simeq 4$. Since the observed line-width of the maser components is $0.5 \text{ km s}^{-1}$, the original line-widths are $\sim 2 \text{ km s}^{-1}$; this represents the sum of quite acceptable thermal and turbulent line broadening. Further, an unsaturated maser with a gain of $e^{18.4}$ requires a line integral of inverted OH molecules given by

$$\int \Delta n_{\text{OH}} \cdot \frac{\nu}{\Delta \nu} \cdot dl = 4.8 \times 10^{20} \text{ cm}^{-2}$$

where $\Delta n_{\text{OH}}$ is the number of inverted OH molecules (Litvak 1969). With $\nu/\Delta \nu = 6 \times 10^5$ we have $\Delta n_{\text{OH}} \cdot dl = 8 \times 10^{14} \text{ cm}^{-2}$. This is 0.5 per cent of the total OH column density calculated above and implies an OH population inversion of 0.5 per cent which is an acceptable value. There is some evidence however that the maser is at least partially saturated (Wilson, Barrett & Moran 1971). In the case
of a saturated maser the column density of inverted molecules is given by (Robinson 1968)

$$\int n_{\text{OH}} \, dl = \frac{2kT_h \Delta \nu \Omega}{\lambda^2 h v W_p} \approx 3 \times 10^{18} \frac{\Omega}{W_p}$$

where $W_p$ is the IR pumping rate and $\Omega$ is the solid angle into which the maser radiates. There is no line narrowing in this case. Taking $W_p$ to be $10^{-3}$ s$^{-1}$, which is within the range proposed by Litvak (1969), we again derive a column density of inverted molecules around $10^{15}$ cm$^{-2}$ by assuming only a modest amount of beaming of the radiation ($\Omega \sim 10^{-1}$). This calculation is rather conjectural however.

### 4.3 A model of OH/IR objects associated with M supergiants

The observations presented above lead to the simple model of the OH/IR object sketched in Fig. 14 which is based on the VY CMa and NML Cyg data. The M supergiant is at the centre of the IR object which probably extends from a

![Diagram](https://example.com/diagram.png)

**Fig. 14.** A schematic plot of a model OH/IR object associated with an M supergiant star. The sizes of the various regions of the object are given; they are not plotted to scale. There will be a merging of the outer parts of the IR region into the OH masering regime. The blue-shifted optical absorption and emission features are probably produced in the IR emitting region.

radial distance $R = 10^{15}$ to $10^{16}$ cm. This will merge into the OH masering region which has an outer radius of $\sim 2 \times 10^{16}$ cm. Extending beyond this to $R \approx 10^{17}$ cm is lower density dust and gas which is responsible for the nebulosity around an object like VY CMa.

The observations show that the OH is expanding outwards at $\sim 40$ km s$^{-1}$ out to a distance of $\sim 2 \times 10^{16}$ cm. The optical blue-shifted emission lines presum-
ably come from nearer the centre where the gas density is higher; Wallerstein (1971a) suggests $n_H$ is somewhere in the range $10^7$ to $5 \times 10^{12}$ cm$^{-3}$. The model outlined in Fig. 14 is axially symmetric. Although it is an idealized representation of an OH/IR object it provides the basis for an estimate of the mass and the rate of mass loss from the system.

If the gas density were constant at $3 \times 10^6$ H atoms cm$^{-3}$ inside a radius of $2 \times 10^{16}$ cm, the total gas mass would be $0.06 M_\odot$. Alternatively with an inverse square law of gas density which is perhaps more realistic the total mass would be $0.16 M_\odot$ out to $2 \times 10^{16}$ cm and $0.8 M_\odot$ out to $10^{17}$ cm radius. Thus the total mass of the circumstellar gas cloud could approach $1.0 M_\odot$, particularly if the cloud extends beyond a radius of $10^{17}$ cm.

The rate of mass flow through a shell of radius of $2 \times 10^{16}$ cm, where OH data show that the expansion velocity is 40 km s$^{-1}$, would be $1.5 \times 10^{-3} M_\odot$ per year. Such a large outflow of material could not come from the star itself but evidently originates in the circumstellar gas cloud.

As pointed out previously (Davies, Masheder & Booth 1972), the observed rotation of the OH cloud gives a high angular momentum per unit mass. With the present parameters the angular momentum of the OH cloud is $\sim 5 \times 10^{58}$ g cm s$^{-1}$. Its angular momentum per unit mass is $\sim 10^{22}$ cm$^2$ s$^{-1}$. This latter value is greater by a factor of $10^2$ to $10^3$ than the high angular momentum stars and is $10^{-2}$ to $10^{-1}$ of that of interstellar material. The high angular momentum argues that the circumstellar clouds of VY CMa and NML Cyg must have contracted directly from the interstellar gas and cannot have originated in the star.

A feature of this model and indeed any of the models proposed for these objects (Woolf 1972; Wilson & Barrett 1971, 1972; Litvak & Dickinson 1972; Dickinson, Bechis & Barrett 1973) is the absence of any optical or radio emission from gas at the far side of the star which should be red-shifted relative to it. The high dust concentration in the central region of the object is believed to obscure the optical emission from the far side. However, this will have no appreciable effect on the radio emission. A possible obscuring mechanism is free–free absorption from thermal electrons produced inside a radius of $10^{16}$ cm where the gas density is $\sim 10^7$ cm$^{-3}$. These electrons could be produced by collisional ionization in the expanding gas or photoelectric ionization of elements such as Na, K, Rb and Cs by the low temperature radiation field of the M supergiant. A free–free optical depth of unity at 18 cm is produced along a radius for $n_e = 10^{-4} n_H$ with an electron temperature of 1000 K. This is discussed further by Davies et al. 1972.

5. CONCLUSIONS

The most significant results of the present observations is the strong evidence for an expanding circumstellar cloud around each object. In addition there is a rotation of 5 km s$^{-1}$ at the periphery of the clouds. A model based on these results suggests a total gas mass in the cloud of $0.1-1 M_\odot$ and a rate of mass efflux of $\sim 10^{-8} M_\odot$ yr$^{-1}$. Both the large mass and the mass efflux argue that the gas could not have originated in the M supergiant but it is part of the pre-stellar nebula. The large angular momentum per unit mass of the cloud compared with stars is further proof of this point. Thus the present observations give a detailed picture of a young luminous star surrounded by a nebula of gas and dust which is being pushed.
outwards by the radiation pressure of the central star. This expanding gas has now reached a distance of $2 \times 10^{16}$ cm from the star.

VX Sag is a similar object to VY CMa and NML Cyg as judged by its optical, infra-red and microwave properties. However, at an assumed distance of 1700 pc its linear dimensions are significantly smaller ($0.2-0.3$). On the other hand, if it were at a greater distance so that its linear size were the same, then its 1612 MHz flux would be two to three times that of VY CMa and NML Cyg, and its optical luminosity would be greater by a factor of $10$ to $10^{2}$ (Hyland et al. 1972).

W 43A is probably of a different type. Apart from its lack of identification with an optical or IR object, its expansion velocity is only $0.2-0.3$ of that of the other objects. It is also smaller if its distance is 2000 pc as adopted in Section 1.

A further important measurement still to be made is the location of the microwave objects relative to the optical and IR sources. Since the present positional accuracy at microwave frequencies is only a few seconds of arc it is not yet possible to place the optical and IR objects within the maps of Figs 4 and 9 to an accuracy of better than the diameter of the 1612 MHz objects. In the discussion it has been assumed that the optical and IR objects are at the centre, but this must be verified observationally.

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