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Narrow polarized components in the OH 1612-MHz maser emission from supergiant OH–IR sources

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Summary. High-resolution OH 1612-MHz spectra are presented of the supergiant OH–IR sources VY CMa, VX Sgr, IRC 10420 and NML Cyg. The spectra have a resolution of 300 Hz. Narrow components in the spectra have linewidths as small as 550 Hz (0.1 km s^{-1}) but there is no evidence for components narrower than this. These results are in accord with present understanding of maser line-narrowing and of the physical conditions in the OH maser regions. Many of the narrow components have an appreciable degree of circular polarization which is not apparent at the lower frequency resolutions usually employed. The circular polarization indicates the presence of magnetic fields of ~1 mG in the circumstellar envelopes, at distances of $\sim 3\times 10^{16}$ cm from the central stars. These fields are strong enough to influence the outflow from the stars, and may help to explain some of the asymmetries which are seen in their circumstellar envelopes.

1 Introduction

The OH maser emission at 1612 MHz from the circumstellar envelopes of OH–IR stars is generally thought to be unpolarized (Elitzur 1982, and references therein). The polarization properties of the 1612-MHz satellite line and the 1665- and 1667-MHz mainlines were studied systematically by Wilson, Barrett & Moran (1970) shortly after the first OH–IR stars were discovered. They measured the degree of polarization in the 1612-MHz line to be typically less than 10 per cent. Two years later Wilson & Barrett (1972) also concluded that the 1612-MHz emission from OH–IR sources is 'essentially unpolarized'. There are only two stars for which significant 1612-MHz polarization has since been reported, and both are very unusual in other respects. Reid *et al.* (1979) detected highly polarized components in the 1612-MHz emission from

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U Ori during its unprecedented maser outburst (Pataki & Kolena 1974), and Mutel *et al.* (1979) and Reid *et al.* (1979) detected ~50 per cent circularly polarized components in the 1612-MHz emission from IRC 10420 whose spectrum has also evolved remarkably (Benson *et al.* 1979). In each case it was possible to estimate the magnetic field strength in the circumstellar envelope from suspected Zeeman components in the OH spectrum.

In this paper we present new measurements of the 1612-MHz spectra of four supergiants, made with a frequency resolution higher than has been available previously. The measurements were made primarily to investigate narrow velocity structure in the OH spectra. As well as resolving the narrowest components for the first time, they also reveal that many narrow components in the 1612-MHz spectra have significant degrees of circular polarization. The implications of this are briefly discussed.

2 Observations

The observations were made in 1983 September using the Jodrell Bank Mk IA radio telescope, which had a beamwidth of 10 arcmin at 18-cm wavelength. The incoming RF signal was split into its components of right- and left-hand circular polarizations (RHC and LHC), and these passed separately through a dual-channel receiver. Cooled FETs provided the first stages of

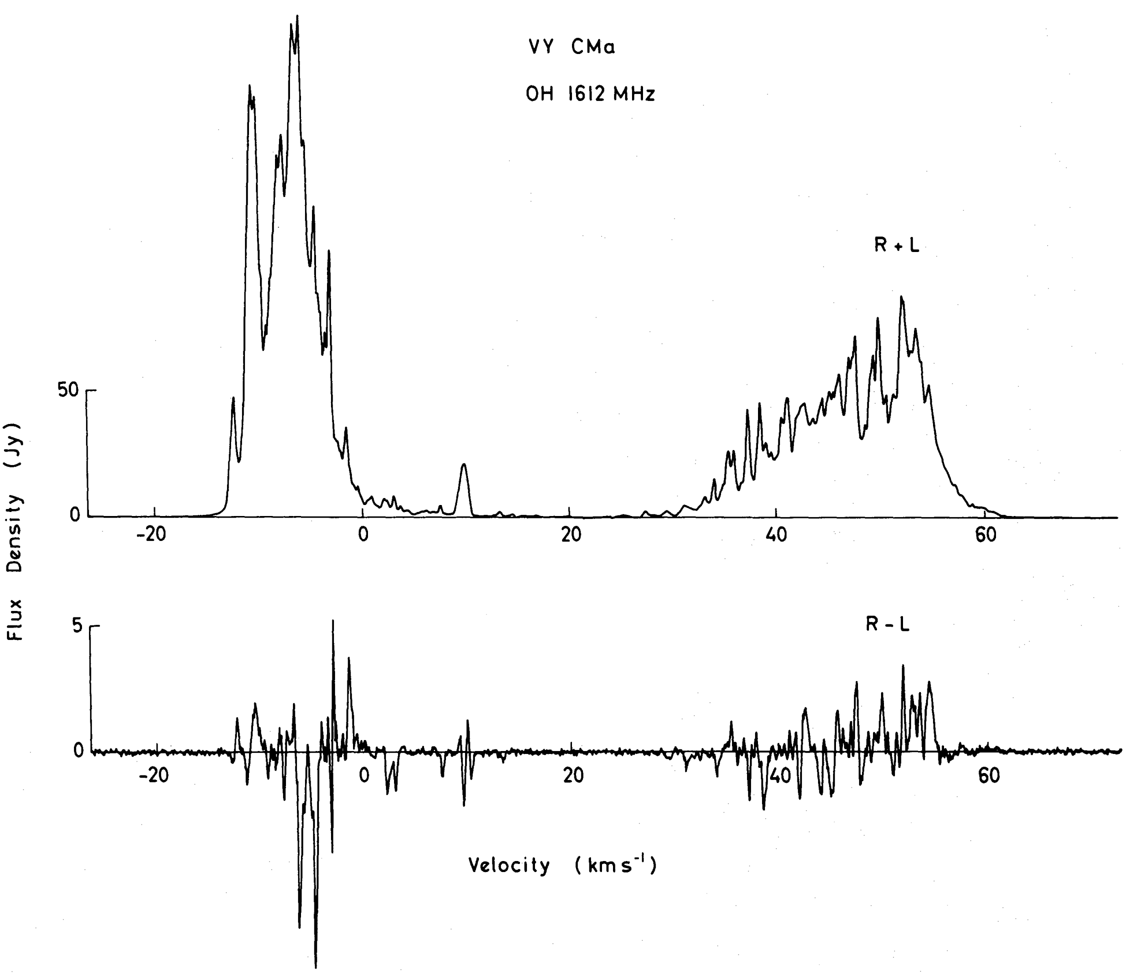

Figure 1. OH 1612-MHz spectrum of VY CMa measured with the Mk IA radio telescope at Jodrell Bank in 1983 September. The frequency resolution is 300 Hz (0.06 km s^{-1}). The two Stokes parameters *S*0 (RHC+LHC) and *S*3 (RHC−LHC) are shown.

amplification and gave a system temperature of ~45 K in each channel. Spectra were taken using a 2^{16}-channel Fourier transform spectrometer. This was built originally as a radio-frequency interference surveillance system for JPL, and has since been made available for SETI observations. The SETI observations made at Jodrell Bank have been reported elsewhere (Downs & Gulkis 1983). The spectrometer carries out fast Fourier transforms in real time by decimation in frequency (Rabiner & Gold 1975). A complete 2^{16}-channel spectrum is computed every 3.2 ms and accumulates in hardware. A frequency resolution of 300 Hz was achieved by clocking at 20 MHz. This corresponds to a velocity resolution of 0.06 km s^{-1} at the OH line frequency of 1612.231 MHz. Spectra were taken in total power mode. In most cases calibration was done by injecting a known amount of noise into the RF system and taking spectra on- and off-source, with and without the calibration signal. A few spectra were calibrated indirectly by comparison with calibrated spectra of lower frequency resolution taken with an autocorrelation spectrometer. The amplitude calibration is accurate to 5 per cent.

The four supergiants VY CMa, VX Sgr, IRC 10420 and NML Cyg were each observed for 26 min in each hand of circular polarization. This gave rms noise levels of ~0.06 K in the final calibrated spectra. The dynamic range of the spectra, defined as the ratio of peak emission to rms noise, was typically over 1000:1.

3 Results

The final OH 1612-MHz spectra are shown in Figs 1–4. For each star the total flux density (right- plus left-hand circular) and the circularly polarized flux density (RHC minus LHC) are plotted. The new spectra reveal numerous narrow line components which are not apparent in previously published spectra of these sources, which were taken with lower frequency resolution. The fine structure is most striking in the case of IRC 10420. The RHC and LHC spectra of the source are plotted separately in Fig. 5 to illustrate this. Individual components with half-power velocity widths approaching 0.10 km s^{-1} can be identified. There is no evidence for unresolved lines narrower than this. For VX Sgr this was confirmed directly by taking observations at 60 Hz resolution, which revealed no new structure in the 1612-MHz spectrum.

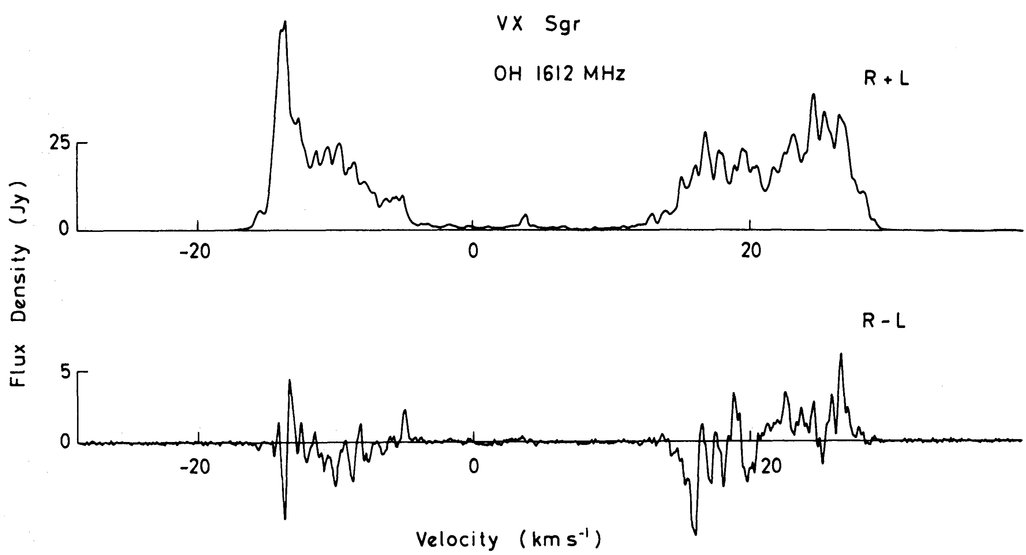

Figure 2. OH 1612-MHz spectrum of VX Sgr measured with the Mk IA radio telescope at Jodrell Bank in 1983 September. The frequency resolution is 300 Hz (0.06 km s^{-1}). The two Stokes parameters *S*0 (RHC+LHC) and *S*3 (RHC−LHC) are shown.

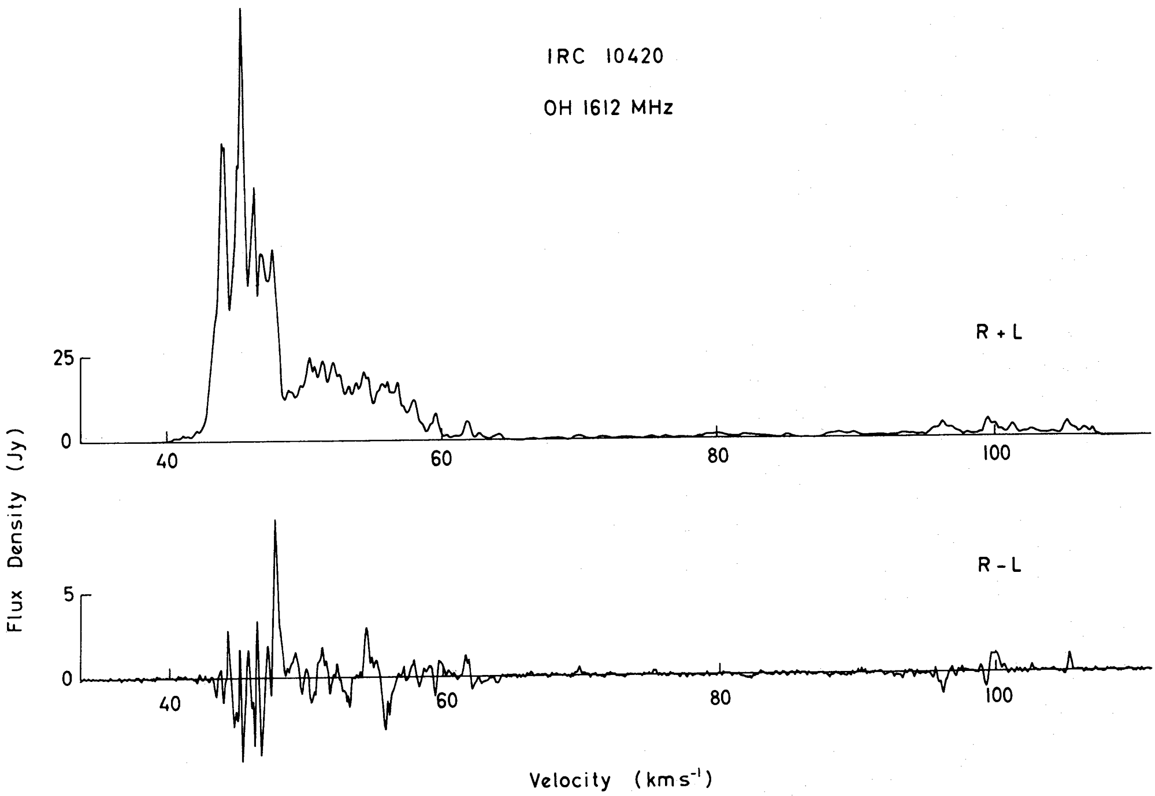

Figure 3. OH 1612-MHz spectrum of IRC 10420 measured with the Mk IA radio telescope at Jodrell Bank in 1983 September. The frequency resolution is 300 Hz (0.06 km s^{-1}). The two Stokes parameters $S0$ (RHC+LHC) and $S3$ (RHC−LHC) are shown. (See also Fig. 5).

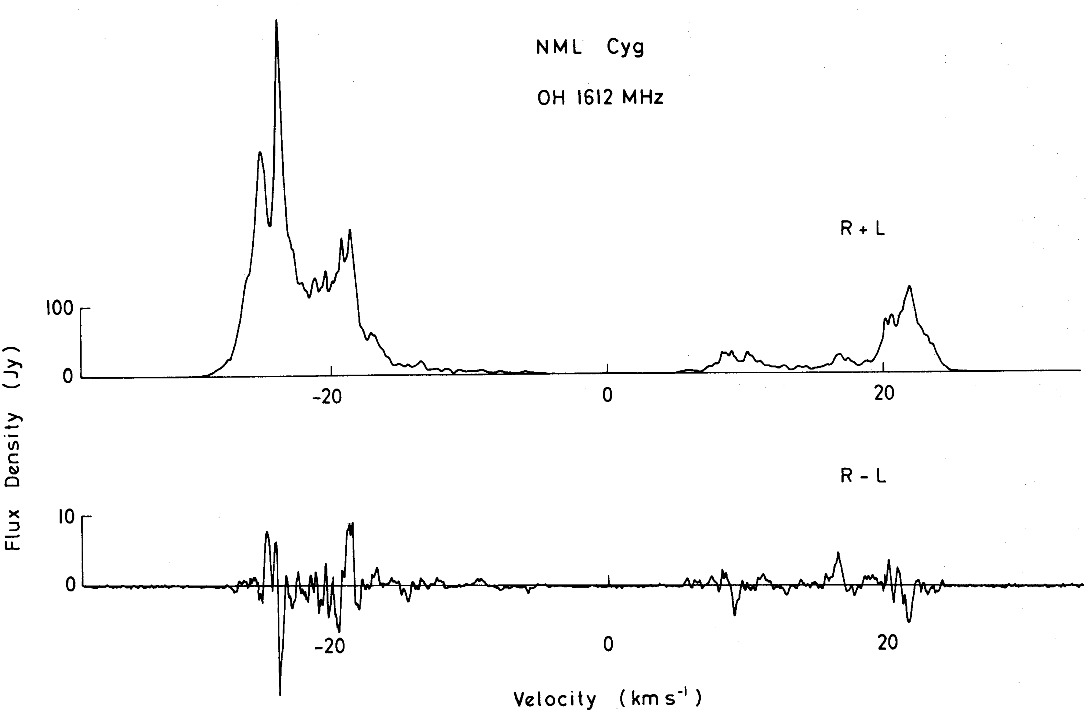

Figure 4. OH 1612-MHz spectrum of NML Cyg measured with the Mk IA radio telescope at Jodrell Bank in 1983 September. The frequency resolution is 300 Hz (0.06 km s^{-1}). The two Stokes parameters $S0$ (RHC+LHC) and $S3$ (RHC−LHC) are shown.

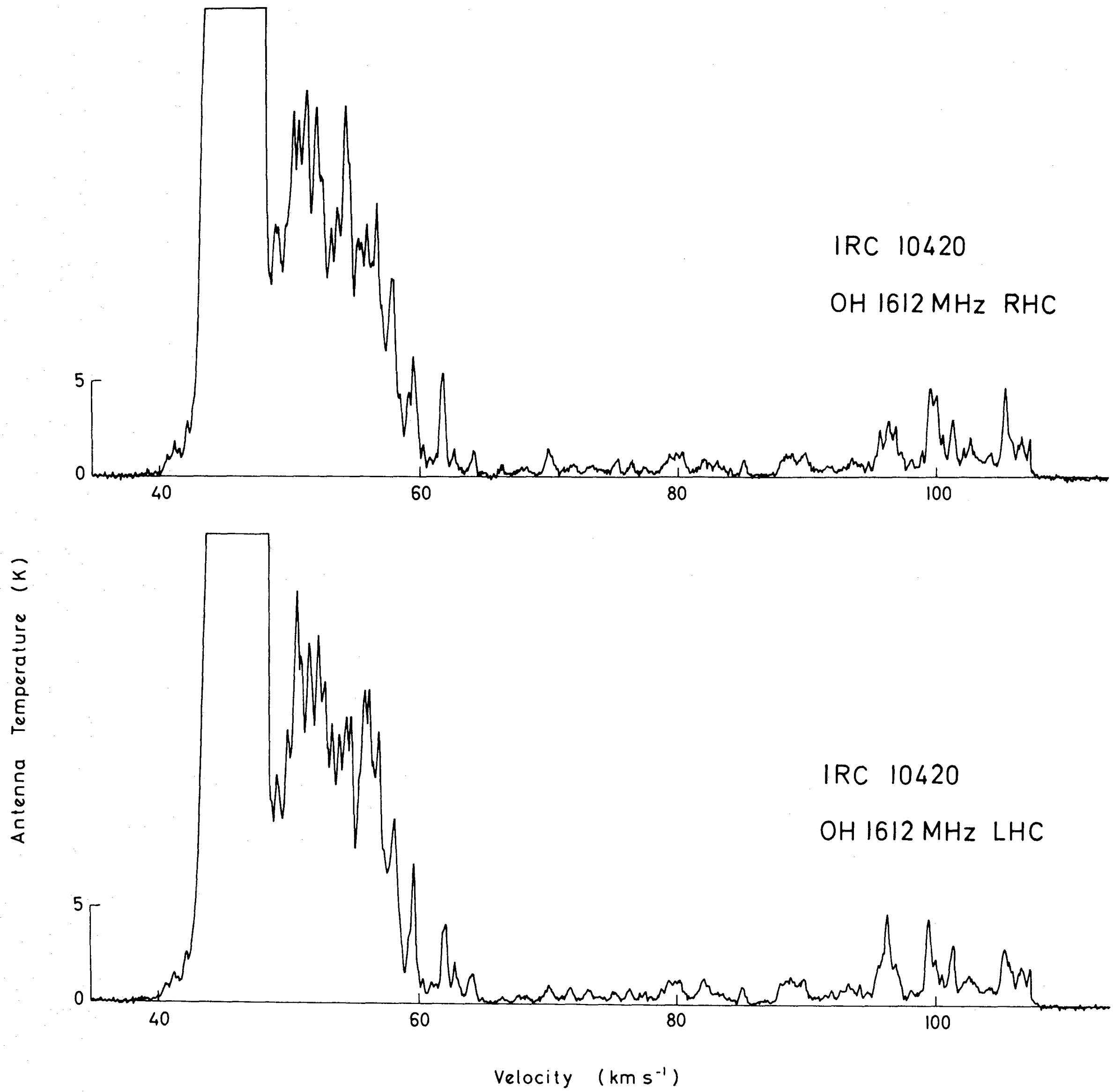

Figure 5. The right- and left-hand circularly polarized spectra of IRC 10420 are plotted separately here on an enlarged scale to show the detailed fine structure in the spectra (*cf.* Fig. 3). The plots have been truncated above an antenna temperature of 25 K.

Many of the narrow line components show significant circular polarization. The fine structure evident in the R–L spectra of Figs 1–4 is due to narrow polarized components which can be identified in the separate RHC and LHC spectra. The degree of polarization reaches 45 per cent in the case of IRC 10420, and each star contains at least one component with 25 per cent circular polarization. The statistics on the numbers of significantly polarized components are given in Table 1. Here we define a significantly polarized component to be one in which the circularly polarized flux density exceeds 1 Jy and the degree of polarization exceeds 10 per cent.

The detection of these narrow polarized components in the 1612-MHz spectra is due to the sensitivity of the present measurements and most importantly to their velocity resolution. To demonstrate the importance of velocity resolution, the spectra were smoothed offline to a resolution of 1 km s^{-1}. IRC 10420 shows no significantly polarized components at this resolution, and no star shows even one 25 per cent polarized component at this resolution. The full statistics

Table 1. Circular polarization of the OH 1612-MHz maser emission from four supergiaant OH–IR sources

Source	VY CMa	VX Sgr	IRC 10420	NML Cyg
Dynamic range of 1612-MHz spectrum	2000:1	700:1	1900:1	4200:1
Maximum circular polarization at 0.06 $km\,s^{-1}$ resolution	36%	38%	45%	24%
Number of significantly polarized features at 0.06 $km\,s^{-1}$ resolution*	14	21	14	18
Maximum circular polarization detected at 1 $km\,s^{-1}$ resolution	22%	22%	<10%	12%
Number of significantly polarized features seen at 1 $km\,s^{-1}$ resolution*	4	3	0	1
Adopted distance	1.5 kpc	1.7 kpc	3.4 kpc	2.0 kpc
1612-MHz OH shell radius r_{OH}	4.8×10^{16} cm	2.1×10^{16} cm	4.5×10^{16} cm 16.5×10^{16} cm	4.4×10^{16} cm 7.3×10^{16} cm
r_{OH}/r_* †	190	90	700 2600	250 420
References	1, 2	3	4, 5	6

*Circularly polarized flux density exceeding 1 Jy and percentage polarization exceeding 10 per cent.
† r_{OH} is the OH shell radius determined from radio interferometry, and r_* is the effective radius of the star estimated from its luminosity and colour temperature. Multiple shell structure is indicated for the sources IRC 10420 and NML Cyg (see Refs 4, 5 & 6).

References:
[1] Bowers, Johnston & Spencer (1983)
[2] Herbig (1970)
[3] Chapman & Cohen (1986)
[4] Bowers (1984)
[5] Mutel *et al.* (1979)
[6] Diamond, Norris & Booth (1984)

are given in Table 1. The fact that the circularly polarized components are not apparent at 1 $km\,s^{-1}$ resolution is perfectly consistent with the conclusions of Wilson *et al.* (1970) and Wilson & Barrett (1972). The degree of circular polarization detected increases steadily as the velocity resolution is improved. This is because the polarized features are generally narrow in velocity width, and because some of them occur in close pairs with opposite hands of circular polarization and very small velocity separations. For example the spectrum of VY CMa (Fig. 1) has two components at velocity of $-3.10\,km\,s^{-1}$ (LHC) and $-2.89\,km\,s^{-1}$ (RHC), whose separation requires a velocity resolution of 0.1 $km\,s^{-1}$ or better. There are other similar examples in Figs 1–4.

It is likely that the true degree of polarization is considerably higher than that revealed by the present measurements. The degree of polarization will generally be underestimated in single-telescope measurements because of the blending of maser emission from several different locations in the circumstellar envelope. This has been directly shown in the case of IRC 10420; VLBI measurement indicate that two 1612-MHz masers may be as much as ~100 per cent circularly polarized (Mutel *et al.* 1979). Finally it should be noted that linear polarization would not have been detected in the present observations.

4 Discussion

4.1 LINEWIDTHS

The present data suggest that there is a lower limit of 0.1 km s^{-1} to the linewidths of individual components in the OH 1612-MHz spectra. There is a simple physical explanation for this. The 1612-MHz masers are known from interferometer measurements to lie in shells r_{OH} at distances of ~100–400 stellar radii from the M supergiants (Table 1) where the gas and dust temperatures are expected to be ~100–500 K (Goldreich & Scoville 1976). For the hotter F supergiant IRC 10420, the masers are located at greater distances where the temperatures are similar (Table 1). Now for OH at 100 K the thermal linewidth is 0.51 km s^{-1}. Maser amplification by a factor of $e^{-\tau}$ (where $\tau<0$ is the optical depth) will produce line-narrowing by a factor $(-\tau)^{1/2}$ for an unsaturated maser, and by no more than this for a saturated maser (Goldreich & Kwan 1974; Litvak 1970). Therefore, with a typical maser gain of $10^{10}=e^{23}$ (Reid & Moran 1981), the line will be narrowed by up to $\sqrt{23}$, giving a minimum linewidth of 0.11 km s^{-1} for the emergent maser line. Thus these simple considerations indicate a minimum linewidth in broad agreement with what is observed.

4.2 POLARIZATION AND MAGNETIC FIELDS

Several of the narrow velocity components seen in the present data occur in close pairs with opposite hands of circular polarization, which suggests Zeeman splitting. The Zeeman pattern for the 1612-MHz transition is complex, involving six σ components and three π components, depending on the viewing angle (see e.g. Davies 1974, fig. 1). It is not possible to identify individual σ or π components in the present data because of the complexity of the spectra, although we note in passing that it might be possible to do so at some stage in the future using observations which combine high frequency resolution with high angular resolution. If we take an average Zeeman splitting for the σ components (Davies 1974, table 1) then the typical velocity separation of 0.5 km s^{-1} for components of opposite circular polarization seen in Figs 1–4 corresponds to a magnetic field strength of 2 mG.

Despite the difficulty in identifying a convincing Zeeman pattern, there is a fairly general argument that magnetic fields of ~1 mG must pervade the OH 1612-MHz maser regions. Deguchi & Watson (1986) have recently shown that the detection of circular polarization itself constitutes evidence for Zeeman splitting, and provides an estimate of the magnetic field strength, regardless of whether a full Zeeman pattern is present. They showed that circular polarization will be produced in a maser with magnetic fields present, provided that the Zeeman splitting is at least comparable with the local linewidth. In the present case the linewidths are 0.1 km s^{-1} or greater, so the detection of circular polarization indicates a field strength of at least ~1 mG. As the circularly polarized components occur throughout most of the velocity range of the OH 1612-MHz emission, this in turn suggests that a field of at least ~1 mG is widespread in the OH maser regions surrounding the stars, at radial distances of $\sim 3\times10^{16}$ cm (Table 1). Such a field can exert a powerful influence on the outflow, as emphasized by Chapman & Cohen (1986). Magnetic fields may in fact be responsible for some of the asymmetries which have been reported in the circumstellar envelopes of these supergiants (e.g. Diamond, Norris & Booth 1984).

The supergiants studied in the present work are a special subgroup of the OH–IR sources. It will be important to see whether the occurrence of 1612-MHz polarization is common in OH–IR sources of other types. The observations currently available in the literature do not exclude the possibility that such polarization is widespread among OH–IR sources, in which case it could be a valuable probe of the magnetic field structure in their circumstellar envelopes.

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Note added in proof

Two other papers reporting narrow velocity components in the OH 1612 MHz spectra of OH–IR sources have come to our attention. B. O. Rönnäng (1972. *Res. Rep. No. 101,* Onsala Space Observatory) has presented observations of NML Cyg and R Aql with 250 Hz resolution, and J. D. Fix (1987. *Astr. J.*, in press) reports observations of IK Tau and IRC 10011 with 600 Hz resolution. In all cases minimum linewidths are 0.2 km s^{-1} or greater, in agreement with the present observations.