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Variations of polarisation properties of OH maser emission from three semiregular variables

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Abstract. We present an analysis of polarimetric observations of the three semiregular variables RT Vir, R Crt and W Hya obtained in the 1665 and 1667 MHz OH maser lines. Circular polarisation data were taken at intervals over a period of 10−14 years. During the two last years of the monitoring program the targets were observed at intervals of 3−4 weeks in circular and linear polarisation. Circular polarisation was dominant, whereas linear polarisation, if detected, was weak. The degree of circular polarisation varied considerably across the maser profiles. It decreased at velocities where strong OH total flux density was observed, most likely due to blending effects. Individual circularly polarised features exhibited various types of changes; some features were transient or showed significant variations on timescales of a few weeks to few months. Other features varied slowly over the period of observations of about 5000 days and polarisation reversal occurred. Net circular polarised emission was detected in the all three stars. Variations of net circular polarisation and the degree of circular polarisation of the maser features of RT Vir implies a well-aligned circumstellar magnetic field. Linearly polarised features preferentially appeared at blue-shifted velocities where they are not suppressed by Faraday rotation. In the blue-shifted 1667 MHz features of RT Vir we observed a systematic increase of degree of linear polarisation associated with a gradual decrease in the degree of circular polarisation. This behaviour was possibly linked to variations in the electron density or propagation effect in the maser regions. It is suggested that changes in the observational characteristics of the polarised maser emission of the studied stars can be caused by turbulence effects in the circumstellar magnetic field and by global magnetic field reversal.

Key words. masers – polarisation – stars: variable – stars: AGB and post-AGB – stars: individual: RT Vir, R Crt, W Hya

1. Introduction

OH mainline masers (1665 and 1667 MHz) emerging from the envelopes of radii of a few 10^{15} cm created by extensive mass loss ($\geq 10^{-7}$ $M_{\odot}$ yr^{-1}) from variable late-type stars are usually polarised (Cohen 1989). OH semiregular variable stars (SRs) appear to be an extreme class of such objects where circular polarisation reached up to 55−75%, even for spectra obtained with a moderate resolution (Szymczak et al. 1995). In two SRs, linearly polarised features were found in the blue-shifted part of their OH spectra (Szymczak et al. 1998, 1999). Therefore, SRs can be particularly good candidates for polarimetric studies. Polarisation of maser emission is thought to be mainly a consequence of the presence of a magnetic field in the regions of line formation which shifts the energies of magnetic sub-levels by the Zeeman effect (Elitzur 1996). Thus, studies of SR stars can provide a means for assessing the properties of the magnetic field in the outer circumstellar regions. In fact, the interferometric measurements of the two SRs, W Hya and R Crt, provided useful information on the strength of the magnetic field and its alignment (Szymczak et al. 1998, 1999). To extend those studies we have analysed data from a long-term monitoring program of OH mainline maser emission from SRs.

This is the second paper in a series relating the OH maser properties of the three semiregulars RT Vir, R Crt and W Hya. The general properties of the OH variations in these stars were recently reported in Paper I (Etoka et al. 2001). Although the all three stars are classified as SRs (Kholopov et al. 1985), RT Vir and R Crt are quite irregular, having poorly defined optical periods of 155 and 160 days respectively. In both stars multiple, OH periods were established (Paper I). In turn, the OH period of W Hya of 362 days is nearly identical to the optical period

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(Kholopov et al. 1985) and this star behaves like a Mira variable.

Here, we present the results for the behaviour of circularly polarised emission over a period comparable to the timescale of gas travel across OH maser shells. During the last two years of the program we also carried out observations in linear polarisation. These data provide the first conclusive evidence for variations in the net circular polarisation, the degree of fractional polarisation, and a relationship between linear and circular polarisations. These observational results are discussed in the context of theoretical relationships between the polarisation properties and magnetic fields, and the propagation of the polarised maser emission.

2. Observational data

The observations were performed with the Nançay radio telescope. The program monitoring RT Vir, R Crt and W Hya started in 1982 April, 1982 January and 1986 January respectively and finished in 1995 November. The details of equipment and observational techniques were given by Etoka et al. (2001). In brief, the targets were observed at 1665 and 1667 MHz with spectral resolutions of 0.07 or 0.14 $\mathrm{km\,s^{-1}}$. For the latter resolution the typical sensitivity was 0.20 Jy. Left- and right-handed polarisations (LHC, RHC) were observed for the whole period of the monitoring. Over the last two years the horizontal and vertical linear polarisations were observed too. Instrumental polarisation of the telescope was continuously monitored and introduced negligible errors in our polarimetric data. The polarisation properties of the Nançay telescope were described in detail by Kazès & Crutcher (1986). However, a small difference in gain between both senses of circular polarisation would produce spurious results. To avoid this we applied a procedure described by Troland & Heiles (1982). The degrees of circular and linear polarisation we will use afterwards in this paper are defined as $m_{\rm c} = 100\% \times (S_{\rm RHC} - S_{\rm LHC})/(S_{\rm RHC} + S_{\rm LHC})$ and $m_{\rm l} = 100\% \times |S_{\rm H} - S_{\rm V}|/(S_{\rm H} + S_{\rm V})$, respectively. Here, $S_{\rm RHC}$ and $S_{\rm LHC}$ are the flux densities of the right- and left-handed circularly polarised emission respectively, while $S_{\rm H}$ and $S_{\rm V}$ are the flux densities in horizontal and veritical polarisation respectively. Prior to 1985, the degree of polarisation had an uncertainty of $\sim$10%. The accuracy of flux density measurements significantly improved during the last years of our program, so that the typical error in the degree of polarisation was 3−4%.

3. Results

3.1. Profile-averaged degrees of polarisation

The OH maser polarisation profiles averaged over the two last years of observations (1993 November–1995 November) are shown in Figs. 1−3. The spectral resolution was 0.07 $\mathrm{km\,s^{-1}}$.

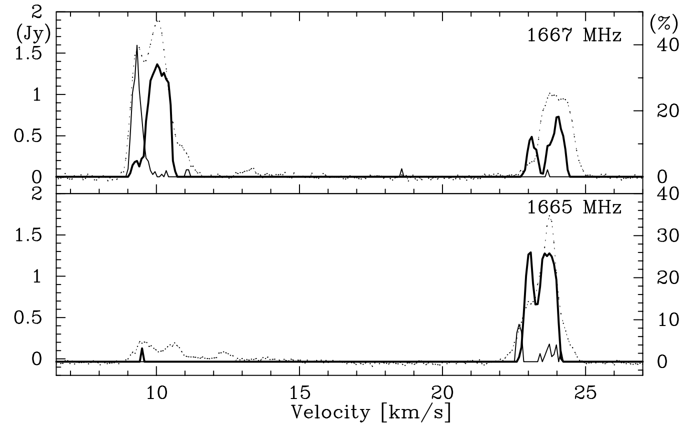

Fig. 1. The average polarisation profiles of the 1667 and 1665 MHz maser lines for RT Vir. The Stokes I profile (dotted line), the profile in circular polarisation (thick line) and in linear polarisation (thin line) are shown. The flux density scale for the I profile is shown on the left and the scale for the percentage of circular or linear polarisation is shown on the right.

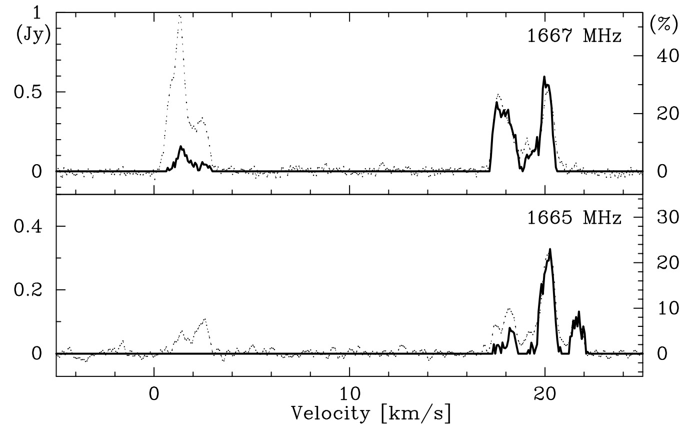

Fig. 2. Same as Fig. 1, but for R Crt. Note the absence of linearly polarised emission.

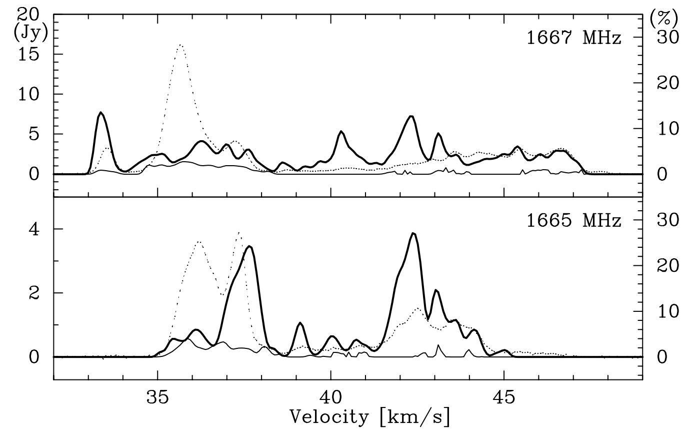

Fig. 3. Same as Fig. 1, but for W Hya.

The blue-shifted 1667 MHz emission of RT Vir was split into two complexes (Fig. 1); the outermost complex centred at 9.2 $\mathrm{km\,s^{-1}}$ was linearly polarised ($m_{\rm l} = 38\%$), while the innermost complex centred at 10 km s^{-1} was circularly polarised (m_c = 34%). No linear polarisation was detected in the red-shifted part of the 1667 MHz spectrum where two circularly polarised features (m_c = 12%, 18%) were seen. The extremely red-shifted emission was unpolarised. The 1665 MHz profile of RT Vir showed a weakly linearly polarised feature (m_l = 8%) centred at 22.7 km s^{-1}. The red-shifted polarisation features at 1665 MHz with m_c = 26% resembled those seen at 1667 MHz with the outermost feature slightly shifted towards lower velocities. The blue-shifted emission at 1665 MHz was unpolarised. We conclude that the degree of circular polarisation varies considerably across the maser profiles of RT Vir. The linearly polarised emission is blue-shifted relative to the circularly polarised emission where both occur in the same part of the spectrum.

No linear polarisation was found in the OH emission of R Crt (Fig. 2). At 1667 MHz, the blue-shifted emission was weakly circularly polarised (m_c = 8%), while m_c of the red-shifted emission was up to 20−30% and the polarisation profile followed well the Stokes I profile. A similar trend was present at 1665 MHz. This suggests that at least the red-shifted emission is composed of intrinsically polarised features and a blending effect is quite weak. Blending may have attenuated the degree of circular polarisation for the blue-shifted emission.

The polarisation profiles of W Hya are shown in Fig. 3. At 1667 MHz, m_c was usually lower than 12% and decreased to about 5% for the blue-shifted parts of the profile with exception of the extremely blue-shifted feature centred at 33.8 km s^{-1}. Weak linear polarisation of a few percent was seen for the blue-shifted emission. Similar characteristics were more clearly visible at 1665 MHz, where for less blue-shifted emission m_c reached values as high as 24−26%. Weak linearly polarised emission appeared in the blue-shifted part of the spectrum only. We suggest that a lowering of m_c at velocities where a strong OH flux density (in Stokes I) is observed is due to blending effects of circularly polarised features.

3.2. $m_c - m_l$ anticorrelation

Variations in the degree of polarisation of the blue-shifted 1667 MHz features of RT Vir are shown in Fig. 4. In spite of cyclic variations of the integrated flux density, the degree of linear polarisation systematically increased, while the degree of circular polarisation decreased. A slight systematic rise of the integrated flux density around consecutive minima is seen. Rapid decreases in m_c and m_l near $JD_m = 4630$ coincided with a diminution of the total OH flux density where an expected maximum was evidently lacking. In this paper $JD_m = JD-2444950$. There was no systematic relationship for the other two sources.

Although the circularly polarised features were observed at velocities different from those of the linearly polarised features, long-term anticorrelated changes in their degrees of polarisation may be associated with slow

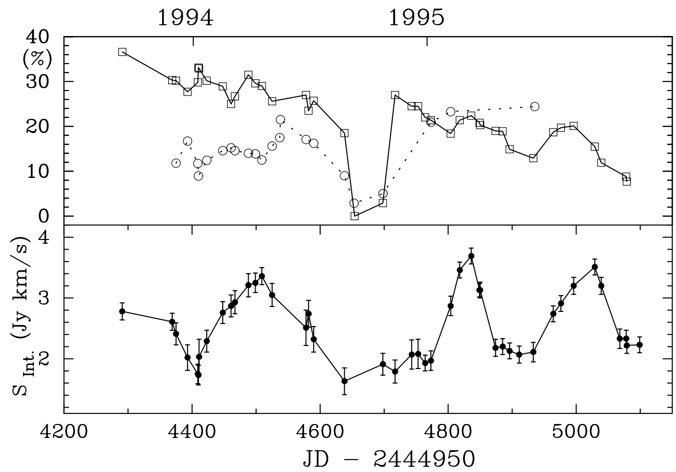

Fig. 4. Anticorrelation between the degrees of linear (circles) and circular (squares) polarisations in the velocity range 8.5−10.5 km s^{-1} for the 1667 MHz maser emission of RT Vir (upper panel). The integrated flux density of the blue-shifted emission (lower panel) is shown for comparison.

variations of physical properties such as a decrease of the electron density in the maser regions which can prevent the emergence of circular polarisation but favours linear polarisation.

3.3. Average Stokes V profiles and degree of circular polarisation

The Stokes V profiles of RT Vir averaged over the whole period of observations are shown in Fig. 5. Plots of the degree of circular polarisation of prominent features as a function of time are also displayed. For both maser lines, the blue-shifted emission was left-hand polarised, whereas the red-shifted emission was right-hand polarised. The 1665 MHz red-shifted feature centred at 21.9 km s^{-1} exhibited moderate m_c variations. This feature disappeared after JD_m = 4160. About 500 days previously, two new features with m_c equals −20% and −35% had appeared at 21 and 23.9 km s^{-1}, respectively. Their degrees of circular polarisation showed an increase up to 30%. In the blue-shifted part of the 1665 MHz spectrum, two features were observed from JD_m = 1400 to 4000 showing m_c up to −50%. Their m_c showed jumps but never reached positive values. Two prominent polarised features in the red-shifted part of the 1667 MHz spectrum were present. The degree of circular polarisation of the feature centred at 21.7 km s^{-1} gradually changed from about −30% in 1982 to about 45% in 1995. An opposite trend was seen for the feature centred at 23.8 km s^{-1}. The 1667 MHz blue-shifted feature centred at 8.9 km s^{-1} was always left-hand polarised and its m_c showed moderate variations. The feature centred at 10.1 km s^{-1} which was initially right-hand polarised became left-hand polarised from JD_m = 1350 with m_c about −40% over the rest of the period of observations.

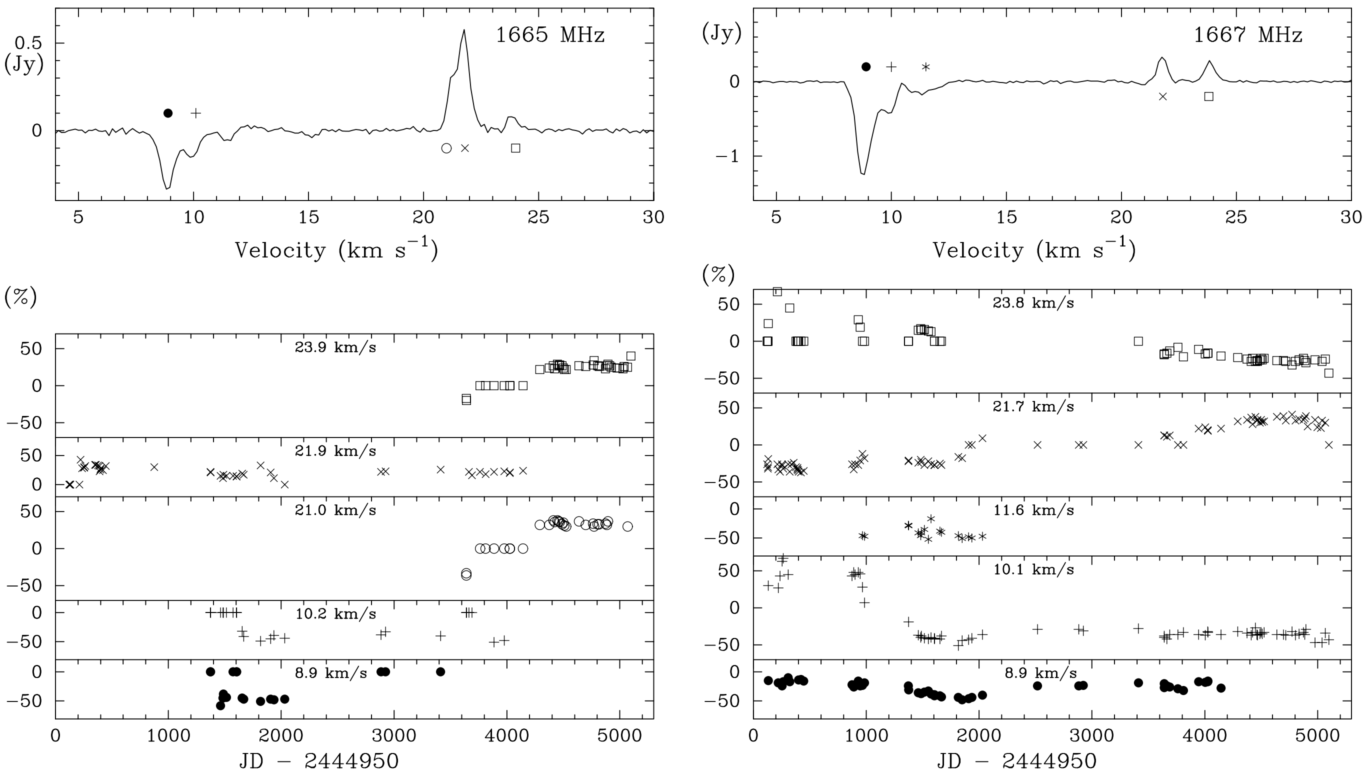

Fig. 5. Average Stokes V (upper panels) and variability of the degree of circular polarisation of selected features (lower panels) for the 1665 and 1667 MHz maser emission of RT Vir. The various symbols stand for the selected features as displayed on the Stokes V profile panel.

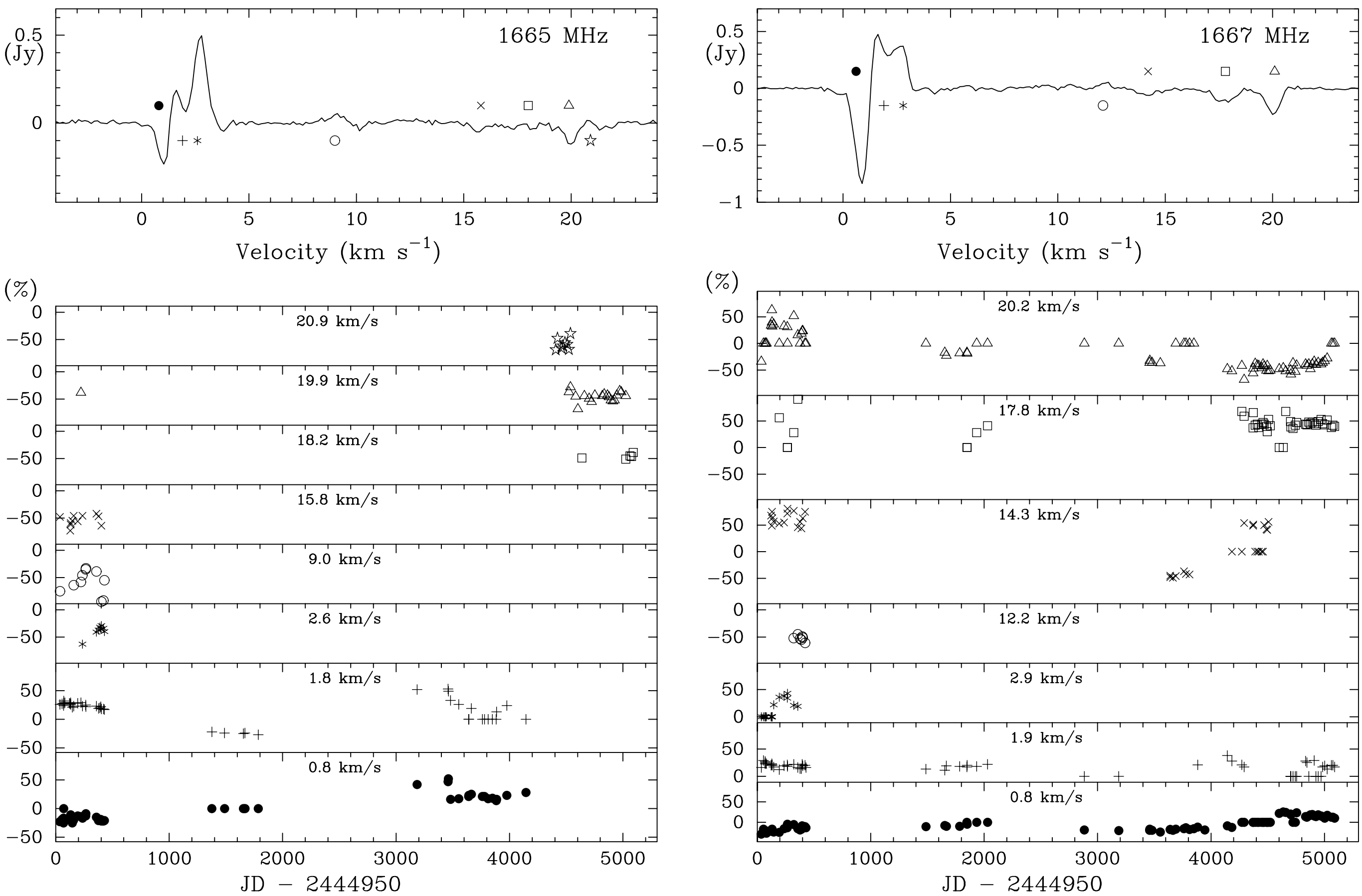

Fig. 6. Same as Fig. 5, but for R Crt.

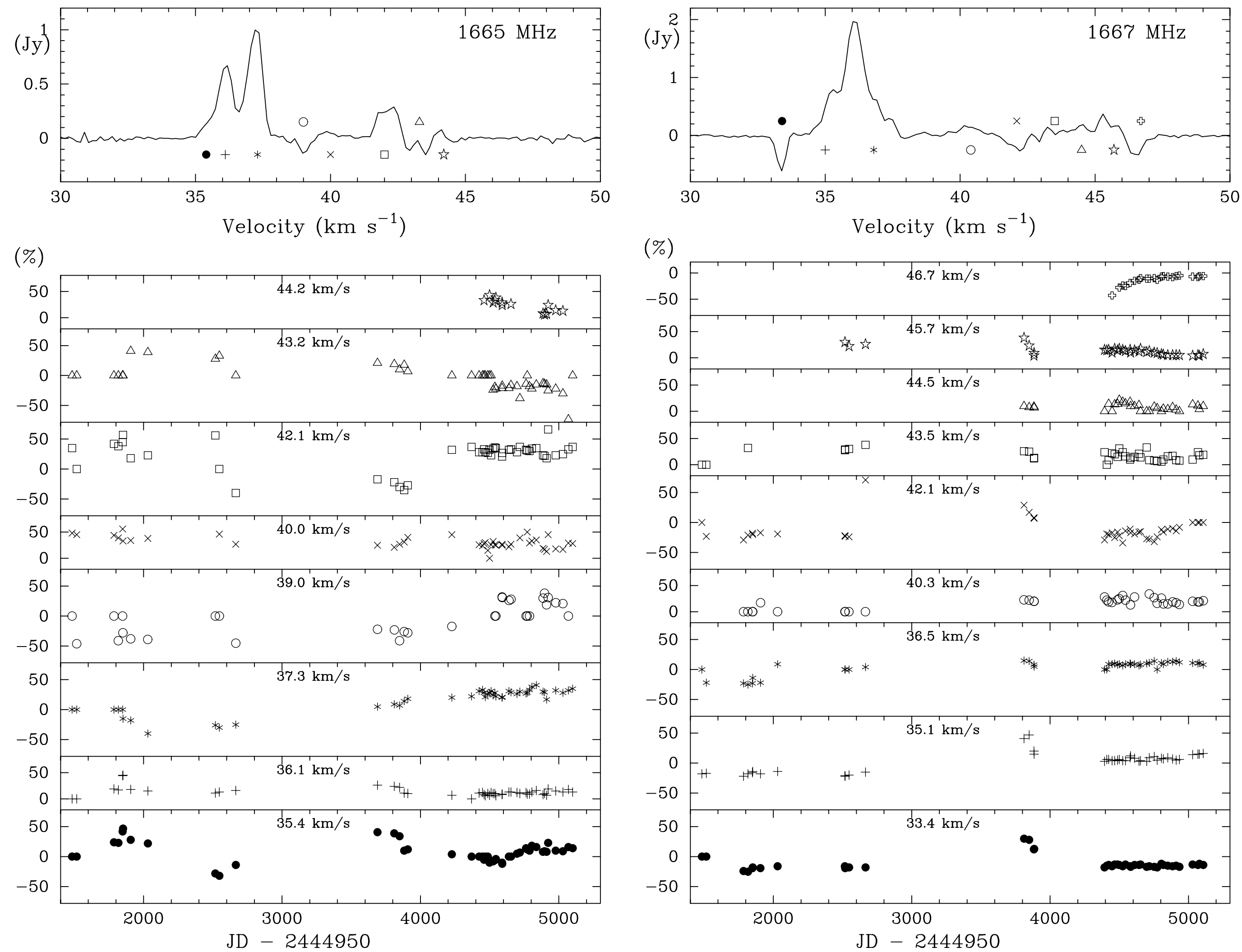

Fig. 7. Same as Fig. 5, but for W Hya.

The time-averaged Stokes V profiles of R Crt are shown in Fig. 6. The temporal behaviour of some circularly polarised features is also presented. At 1665 MHz, the red-shifted features are observed mainly during the last two years of observations and their m_c were usually about or lower than −50%. In contrast, the blue-shifted features were visible before $\mathrm{JD}_m = 4200$. The feature centred at 0.8 km s^{-1} was formerly left-hand polarised (with m_c of about −20%), but after $\mathrm{JD}_m = 3100$ it was right-hand polarised (with m_c ranging from 25% to 50%). The feature centred at 1.8 km s^{-1} was most of the time right-hand polarised (with $m_\mathrm{c} < 50\%$) but near $\mathrm{JD}_m = 1600$ the polarisation reversed. The averaged Stokes V profile at 1667 MHz had a similar shape to that at 1665 MHz. m_c of the red-shifted features showed long-term variations with considerable dispersion on timescale of 50–100 days. A reversal of polarisation was observed for the feature centred at 20.2 km s^{-1}. The features located in the innermost parts of the spectrum were transient and showed considerable variations in m_c. Variations of m_c of the blue-shifted features were usually smoothed. The feature centred at 0.8 km s^{-1} showed a gradual drift in m_c from −30% to 25% over the whole interval of observations, whereas the neighbouring feature centred at 1.9 km s^{-1} always showed a positive m_c.

The OH maser spectra in Stokes V of W Hya showed several circularly polarised features (Fig. 7). The m_c variations of some of them are displayed. For the red-shifted features at 1665 MHz, m_c showed changes over a few hundred days superimposed with long-term variations. Most of the time, the blue-shifted features showed smooth changes in m_c. Variations of m_c of the 1667 MHz features were smoother than those of the 1665 MHz spectrum. This suggests that variations of the degree of circular polarisation may depend on the distance of maser regions from the central star. The amplitudes of m_c of the 1667 MHz features were lower than those observed for the 1665 MHz features.

We conclude that the degree of circular polarisation of the OH maser features of the studied semiregulars exhibited a variety of behaviours. Some circularly polarised features are transient; they vanish and reappear at other epochs. Long-lasting features show moderate variations in their m_c, superimposed on short changes (50–100 days)

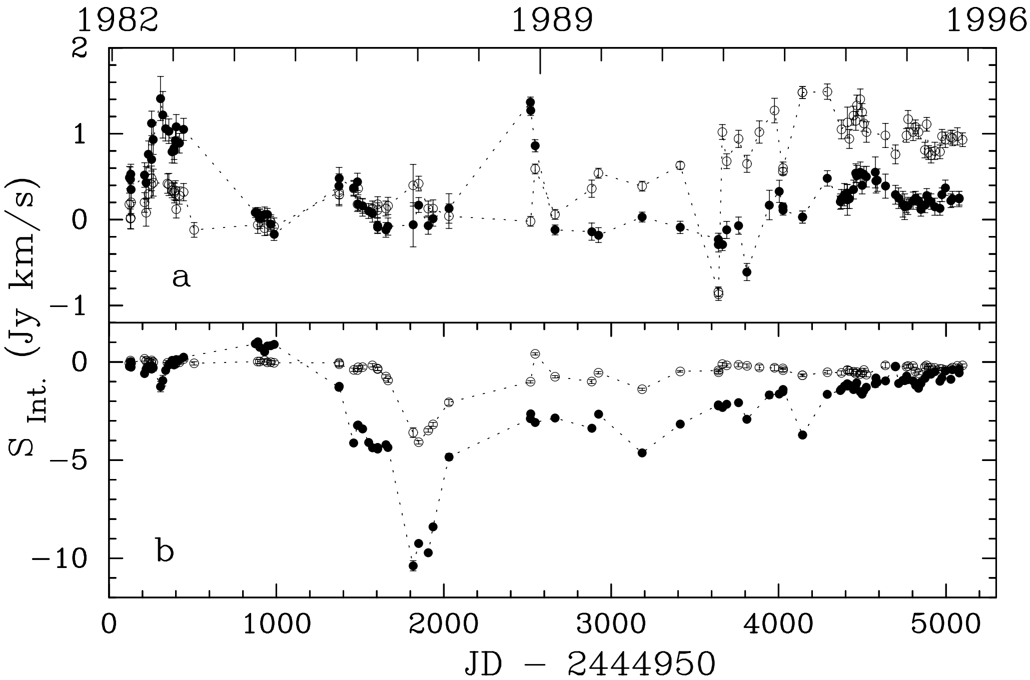

Fig. 8. Variability of the integrated flux densities in Stokes V of RT Vir at 1667 (filled circles) and 1665 MHz (open circles) for the red-shifted **a)** and blue-shifted **b)** emissions.

of high amplitude. A reversal of circular polarisation of these permanent features occurs over a period comparable to the whole interval of observations, i.e. of more than 5000 days.

3.4. Net circular polarisation

The variability of the integrated flux in Stokes V of RT Vir is shown in Fig. 8. The red-shifted emission in Stokes V of both lines followed the changes observed in the total flux density (see Fig. 14 of Paper I). The same trend was observed for the blue-shifted emission. Thus, in the envelope of RT Vir, the maser emission of one sense of the circular polarisation was preferentially propagated. It is interesting that the net circular polarisation in the red-shifted part of the spectrum is in the opposite sense to that observed in the blue-shifted part. This can be an indication of a well ordered magnetic field in the same direction for both the front and back parts of the envelope.

The variability curves of the integrated flux in Stokes V for the red- and blue-shifted parts of the 1665 and 1667 MHz line profiles of R Crt are shown in Fig. 9. The red-shifted emission of both lines behaved very similarly after November 1993 where a net LHC emission was observed. Furthermore, comparison with Fig. 12 of Paper I indicates that LHC emission constituted about 70% of the total density flux. At 1665 MHz, the red-shifted emission was almost unpolarised over the 11 years of observations before November 1993 while the red-shifted emission at 1667 MHz exhibited some changes in the sign of its degree of circular polarisation. The blue-shifted emission varied mostly independently for both lines but significant rises of the net circular polarisation were usually correlated with the total flux density. We conclude that the changes in the OH integrated flux emission of R Crt reflect mostly the changes of the circularly polarised emission. Moreover, the presence of non-zero integrated flux in Stokes V implies that for R Crt a mechanism capable of producing net polarisation (Cook 1975; Deguchi & Watson 1986) must be at work.

In the best sampled interval of observations of W Hya, the integrated flux in Stokes V showed considerable variations in both lines (Fig. 10). Increases of circular polarisation in the red-shifted part of the 1667 MHz spectrum were well correlated with the maxima of the total integrated flux (Fig. 13 of Paper I). There was only weak evidence for a similar correlation at 1665 MHz. This is likely because the 1665 MHz emission comes from more inner regions than the 1667 MHz emission, where systematic variations may be masked by turbulence or shock effects. The net circular polarisation in the blue-shifted part of the spectra in both lines exhibited a rough anticorrelation with the total integrated flux. Therefore, an increase of the OH flux density was correlated with a reduction of the amount of circular polarisation of the emission from the front part of the envelope. It is possible that blending of highly polarised features is one cause of this effect. Our data suggest that spectral blending does not affect significantly the red-shifted emission at 1667 MHz.

4. Discussion

4.1. Relationship between circular and linear polarisations

The main finding of our polarimetric measurements is that individual polarised features exhibited various types

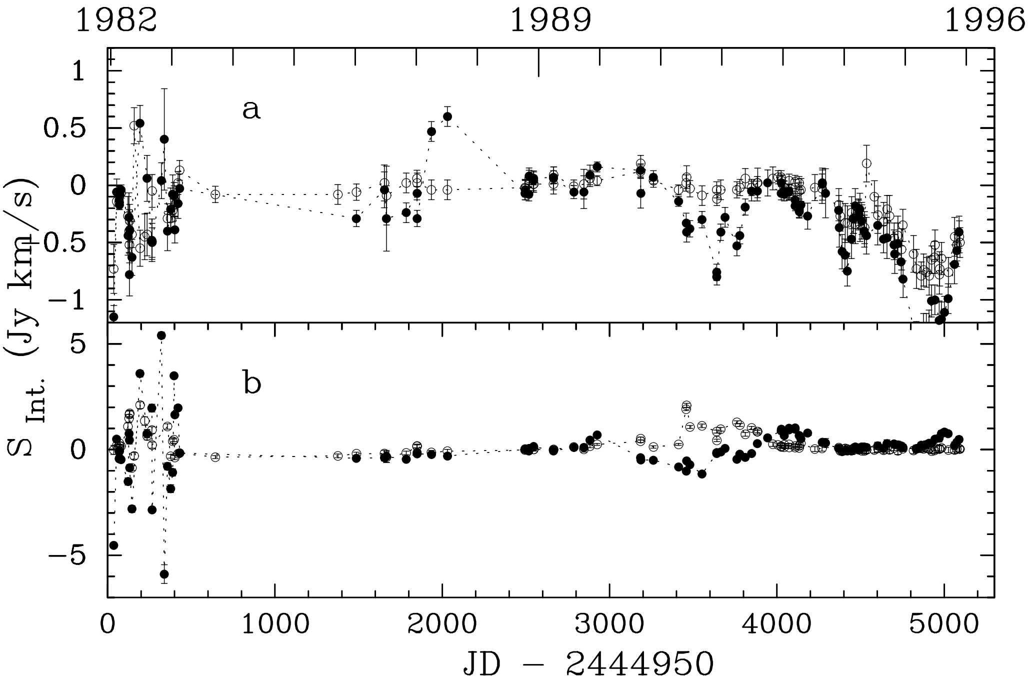

Fig. 9. Same as in Fig. 8, but for R Crt.

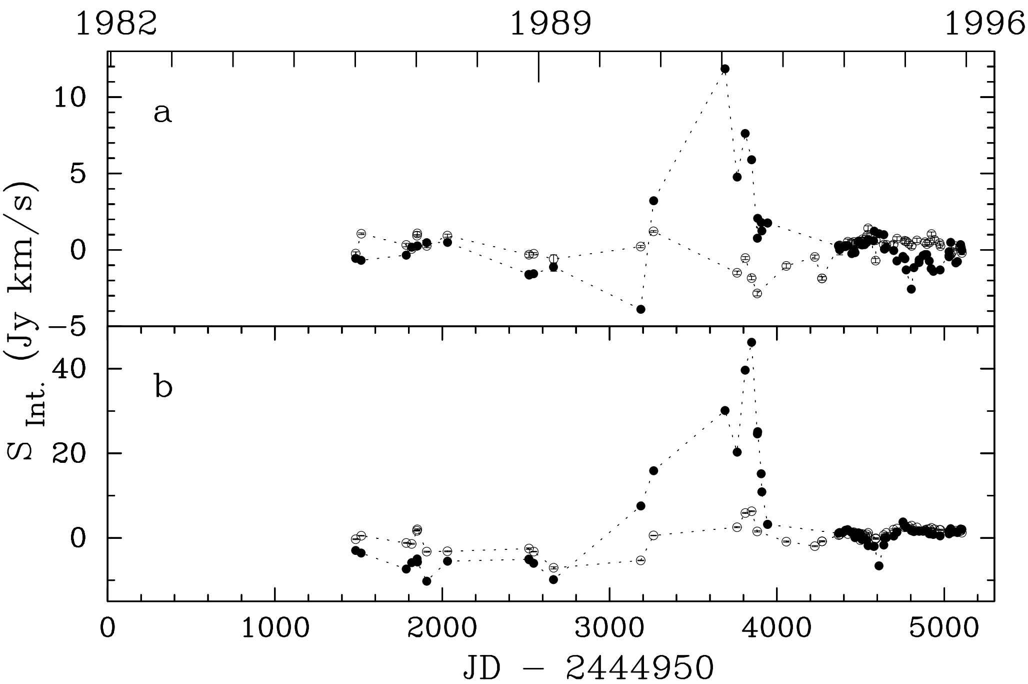

Fig. 10. Same as in Fig. 8, but for W Hya.

of variations. An intriguing behaviour showed the blue-shifted 1667 MHz emission of RT Vir (Fig. 4). For this emission the anticorrelation between $m_{\rm c}$ and $m_{\rm l}$ occurred over the two last years of monitoring. No correlation between the changes in the degree of polarisation and periodic variations in the integrated OH flux density was seen. However, we noted a slight increase of the integrated OH flux density during consecutive minima. A decrease of $m_{\rm c}$ with an increase of total flux density is expected for a thick envelope where blending of polarised features can play a role. Furthermore, the linear and circular polarisations of this emission disappear ($\mathrm{JD}_m = 4630$, Fig. 4) when the maser emission is not sustained in a regular manner. The behaviour of the blue-shifted 1667 MHz emission of RT Vir may imply that the polarisation is an intensity-independent process.

Magnetic fields are thought to generate maser polarisation (Goldreich et al. 1973). The linearly polarised components (π) are expected to be suppressed for a wide range of the ratio of the Zeeman splitting to the Doppler line width and saturated emission. As shown in Paper I, OH emission from RT Vir is unsaturated, at least during outburst activity, so that the conditions for suppression of the linearly polarised features are fulfilled. Therefore, linearly polarised components propagating away from the star are likely to be unaffected by internal Faraday rotation as the electron density should drop with distance from the central star. In contrast, in inner regions of the envelope, those components are destroyed resulting in an increase of circular polarisation. This explanation is consistent with the observation that the linearly polarised emission almost always appears at the extreme blue-shifted velocities for RT Vir and W Hya, whereas the circularly polarised components (σ) occur in the innermost parts of the double-peaked spectrum. Similar observational evidence was also provided by interferometric studies (Szymczak et al. 1998, 1999). It is likely that those properties are usual for Mira-type OH emitters. If the above interpretation of the Faraday effect on linear polarisation is correct, a gradual increase of $m_{\rm l}$ together with a decrease of $m_{\rm c}$ implies that the electron density slowly decreases over the period of observations. Full polarimetric observations of other stars would be interesting in order to verify this assumption.

Because the propagation of π and σ components of Zeeman pattern is allowed perpendicular and parallel to the lines of magnetic fields respectively (Elitzur 1996), the changes observed in polarisation properties of the blue-shifted 1667 MHz emission of RT Vir can be due to changes in the strength and/or configuration of circumstellar magnetic field. Polarimetric observations with high angular resolutions would be helpful to test this hypothesis.

4.2. Polarising mechanisms

Evidence for considerable variations of the net circular polarisation of OH maser emission from the studied semiregular variables is one of our most important findings. In R Crt and RT Vir, these variations were correlated with the changes observed in the total integrated flux, whereas in W Hya anticorrelation was seen at least for the blue-shifted emission. If the primary mechanism of polarisation is the Zeeman effect, then a non-zero value of the integrated flux in Stokes V indicates that one of the circular polarisations is more amplified. Enhancement of the optical depth of one sense of the circular polarisation over that of the opposite sense due to matching of the gradients of magnetic field and velocity (Cook 1975), or the overlap of the Zeeman component due to the velocity gradient alone (Deguchi & Watson 1986), are probably involved. Because in the studied semiregulars, the OH mainline emission arises at the distance of 40−130 au from the central star (Szymczak et al. 1998, 1999), it is likely that the magnetic field strength is high enough to split lines of opposite circular polarisation by more than a thermal linewidth. In this case, if it is confirmed that the components are spatially coincident, the magnetic field strength along the line of sight can be estimated.

Growth of one sense of circular polarisation in R Crt and RT Vir is mainly responsible for the OH flux density increase. This suggests the presence of a fairly ordered circumstellar magnetic field in thin OH envelopes. RT Vir is an interesting source since one sense of the circular polarisation apparently propagates preferentially on one side of the envelope, that is, LHC emission dominates at blue-shifted velocities while RHC emission dominates at red-shifted velocities. A natural explanation could be the Cook mechanism for an envelope with a global magnetic field oriented towards the observer. In such a case, σ^- components (LHC) of Zeeman patterns will overlap, while σ^+ components (RHC) will diminish at the front of the envelope. The opposite case will occur at the back of the envelope. Similar arguments successfully explained a segregation of the circularly polarised OH masers in VX Sgr (Zell & Fix 1996) for a bipolar magnetic field. In the case of RT Vir we do not assume a field configuration but only its direction.

Preferential amplification of one sense of circular polarisation probably operates also in W Hya, but due to a larger thickness of the OH shell, the net circular polarisation decreases during OH maxima as a result of spectral blending of individual emitting elements. In the two other targets, the blending is weak if any, possibly due to a smaller number of maser elements in relatively thin envelopes.

In Paper I, we presented the periodic variations of the total OH flux density of the same three semiregulars. In general, there is no obvious relationship between these variations and changes in the degree of circular polarisation of the most prominent individual features. This can imply that circularly polarised features arise due to propagation effects such as those issuing from a correlation between the gradient of magnetic fields and the outflow velocity (Cook 1975) or a correlation of velocity gradients alone (Deguchi & Watson 1986). Our data for W Hya suggest that these effects can be partly masked for spectra obtained with moderate velocity resolutions. Nevertheless, rapid variation in the degree of circular polarisation observed for some features on time-scales of a few months can be intrinsic to the masers. These can be due to plasma turbulence effects which may alter the magnetic field in the OH maser region, suppressing the maser amplification via the Cook mechanism (Palen & Fix 2000). For long-lasting polarised features, we found a reversal of circular polarisation on a time-scale comparable to the duration of our monitoring program. If the Cook mechanism is responsible for the growth of one component of a Zeeman pair, such an effect could be expected for a circumstellar bipolar magnetic field which reverses its configuration over a period longer than 5000 days.

5. Conclusions

Variations in the polarisation properties of OH mainline emission from three semiregular variables have been observed over 10−14 years. The main conclusions are summarised as follows:

1. Circular polarisation dominates in the all maser sources. The degree of circular polarisation of maser features varied considerably on different timescales. Variations over a few months can be caused by turbulence effects in the circumstellar magnetic field, whereas smooth variations over 5000 days can be due to a reversal in magnetic field configuration or secular changes in its strength.

2. Linearly polarised features are generally weak and preferentially occur at the blue-shifted velocities where they are not strongly affected by internal Faraday rotation.

3. Anticorrelation between the degrees of circular and linear polarisations was found for the blue-shifted features of RT Vir at 1667 MHz. A slow increase of m_{l} and a decrease of m_{c} is interpreted as due to a lowering of the electron density with distance from the star during the period of observations. These variations are not correlated with cyclic changes of the total integrated flux density and may suggest that the polarisation is an intensity-independent process.

4. Changes of the net circular polarisation are well correlated with changes of the integrated flux density. This indicates that mechanisms of preferential amplification of one sense of circular polarisation operate in the OH envelopes of the studied sources. Variations of polarisation properties of RT Vir suggest a circumstellar magnetic field well aligned relative to the line of sight.

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