Polarimetry of ST LMi: discovery of a second accreting pole

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ABSTRACT
We have obtained simultaneous multiband photometric and polarimetric light curves for ST LMi (CWI103 + 254) in the visible range and the near-infrared on three occasions. These clearly show the presence of previously unobserved accretion at or near the second magnetic pole of the white dwarf. The secondary accretion region is seen only in the H and J bands, from which we infer a lower accretion rate than for the primary region.

Key words: accretion, accretion discs - polarization - radiation mechanisms: cyclotron and synchrotron - stars: individual: ST LMi - novae, cataclysmic variables - white dwarfs.

1 INTRODUCTION

ST LMi is a member of a class of cataclysmic variables (CVs) known as AM Her systems, after the archetype. These differ from the other classes of CV in that the white dwarf has a large enough magnetic field to prevent the formation of an accretion disc around the primary. The material lost from the secondary is channelled directly on to the surface of the white dwarf at, or near, the magnetic pole. Several observational features distinguish AM Her stars from other CVs (see for example Bailey 1985, Wickramasinghe 1988 and Cropper 1990 for recent reviews) but their main distinguishing feature is the presence of strong variable linear and circular polarization. This is produced by cyclotron radiation from the infalling shock-heated plasma as it moves along the field lines near the surface of the primary.

The interaction of the stream from the secondary with the magnetic field is a complex process. Initially, the stream was thought to follow the field lines threading the L 1 point down to the surface of the primary, but this perception changed when Liebert & Stockman (1985) suggested that a large stagnation region forms between the two stars as the magnetic field is stretched and stressed by the infalling stream. The gas in this reservoir then threads on to the magnetic field and accretes on to the white dwarf. The consequences of this scenario are that the accretion region will be displaced from the magnetic pole, and accretion may not be radial. The extent and position of the reservoir determines the relative accretion rates at the two magnetic poles.

AM Her systems fall naturally into two groups depending on whether only one magnetic pole is observed during the course of the orbital period (one-pole systems) or whether both poles will be seen (two-pole systems). VV Pup was the first AM Her object to show any observational evidence (from circular polarimetry) of accretion on to both poles (see Liebert & Stockman 1979). VV Pup has a 100-min period, close to the 114-min period of ST LMi, and has similar light variations showing sharp declines in brightness as the main accreting pole passes over the limb and out of view. A recent study (Meggitt & Wickramasinghe 1989) of the linear polarization curves of the one-pole systems EF Eri and AM Her has demonstrated the existence of two accretion regions in those objects and also yielded sufficient information to model the field geometry. These investigations have been important in providing some estimates of the relative accretion rates at the two magnetic poles and the relative positions of the accretion regions. From its relatively simple behaviour at optical wavelengths, ST LMi was considered to be the archetypal one-pole accretor (Stockman et al. 1983; Schmidt, Stockman & Grandi 1983, hereafter SSG); here, however, we present evidence that even this system accretes at both magnetic poles.

Recent observational studies of ST LMi include Bailey et al. (1985, hereafter BWS) and Cropper (1986, hereafter MSC).

2 OBSERVATIONS

Observations were made with the Mk 1 Hatfield Polarimeter (Bailey & Hough 1982) on the 3.9-m telescope of the Anglo-Australian Observatory on 1986 January 7 and 8, 1986 June 29, and 1987 February 24 and 25. The phase
coverage of observations is given in Table 1. The polarimeter was modified to allow simultaneous observations in the infrared and two visual bands instead of the previous one infrared and one visual band. Figs 1 to 5 show the observations of $B$, $R_c$ and $H$ from January 8, and $J$ and $I_c$ bands from February 25 ($c$ denotes the Cousins system, see Cousins 1980), phased during the ephemeris of MSC. The light curves are repeated over two whole cycles for clarity.

Linear polarization is a positive definite quantity and observational uncertainties bias the mean. The linear polarization data are corrected for the bias thus introduced (Wardle & Kronberg 1974).

3 GENERAL COMMENTS ON THE LIGHT CURVES

The $B$ magnitude on January 8 (Fig. 1) varies almost sinusoidally between 17.1 and 16.5. The range of the orbital variation of $\sim 0.7$ mag is consistent with the two Miller (1982) light curves but our observations are about 0.5 and 1.0 mag fainter. Photographic $B$-band photometry (Gotz 1986) shows that the object brightened by about 1.5 mag in the 30 d after our January observations and then declined again slightly to its mean brightness state before our June observations. Circular polarization of $\sim -7$ to $-8$ per cent appears in a fairly well-defined peak between $\phi_{\text{orb}} = 0.7$ and 1.0, for all dates, extending over part of the photometric maximum. These values are somewhat larger in magnitude than BWS's $-2$ to $-3$ per cent. Linear polarization in all cases is noisy (in the circular mode of operation of the Hatfield Polarimeter the efficiencies for the linear polarization are half those for the circular). At most, there is marginal detection of linear polarization in the $B$ band of less than 5 per cent with some evidence for systematic position angle variation between $\phi_{\text{orb}} = 0.7$–0.2 on January 8. Using larger phase bins to improve the signal-to-noise ratio does not help because the phase resolution becomes too coarse.

On January 8 (Fig. 2) the $R_c$-band brightness increases linearly between phases 0.35 and 0.70, and then rises rapidly over 0.06 of the period, $P_{\text{orb}}$, to an almost flat maximum of 0.2 $P_{\text{orb}}$ duration, the bright phase. The rapid fall from maximum, although over a greater magnitude range than the rise (1.7 as opposed to 1.0), also takes 0.06 $P_{\text{orb}}$. Thereafter the brightness falls very slowly until $\phi_{\text{orb}} = 0.35$. The amplitude of 2.0 mag is consistent with the observations of Stockman et al. (1983) although the light curve is 0.2 to 0.4 mag fainter. The linear polarization shows the double peak typical of ST LMi (MSC), with peaks cophasal with the steep rise and fall in the photometry. It is also significantly non-zero through most of the cycle as is evident from systematic variations in position angle. These variations are consistent with MSC's observations of a broad red band and are in good agreement in the latter part of the bright phase. However, MSC observed linear polarization (with well-defined position angle) from $\phi_{\text{orb}} = 0.58$ to 0.05, somewhat earlier than our observations from $\phi_{\text{orb}} = 0.70$ to 0.15, although the positions of the linear polarization peaks are in excellent agreement. The $R_c$-band circular polarization starts to fall from zero about 0.05±0.01 $P_{\text{orb}}$ (6±1 min) before the steep photometric rise to maximum, unlike in MSC's polarimetry, where the two events appear to be simultaneous. The circular polarization reaches $-23$ per cent.

$I_c$-band data were taken during the February and June runs. The brightness on June 29 varied from 15.5 to 13.6 mag and on February 25 (Fig. 3) from 16.1 to 13.8 mag. Both the brightness and the phase of the maxima were different though all other features agree excellently and the circular polarization on February 25 reached $-20$ per cent during the bright phase on both occasions.

The $H$ band was observed on all three occasions but full phase coverage was obtained only on February 25, as shown in Fig. 5. The photometry curves vary from 13.9 to 13.0 mag on January 8, 13.5 to 12.4 on June 29, and 14.7 to 13.7 on February 24. Both the range and level on January 8 agree well with the brighter of BWS's two $H$-band curves.

The most striking aspect of these observations is the $H$-band circular polarization. BWS detected no circular polarization during the bright phase in $H$ to a limit of about 2 per cent, but Fig. 5 clearly shows polarization up to between 10 and 15 per cent in the positive sense during the faint phase. A primary minimum of $\sim 0$ per cent is visible at $\phi_{\text{orb}} = 0.9$, the photometric maximum, and a secondary minimum may be discerned between $\phi_{\text{orb}} = 0.2$ and 0.4. Although the light curve does not extend beyond $\phi_{\text{orb}} = 0.35$ on January 7 (not shown), the peak around $\phi_{\text{orb}} = 0.1$ is present on both occasions. Positive polarization is again seen in the limited phase coverage on other dates. In June it decreased from 18±2 per cent near the start of the observation to $\sim 0$ per cent at $\phi_{\text{orb}} = 0.85$ and increased again to $\sim 15$ per cent at $\phi_{\text{orb}} = 0.05$ before observations became too noisy. The February 24 data (not shown) are noisy but show a maximum of $> 10$ per cent at $\phi_{\text{orb}} = 0.55$ and a minimum of $\sim 0$ per cent at $\phi_{\text{orb}} = 0.8$ to 0.9.

The $H$, $I_c$ and $B$ bands were each observed on more than one occasion and consistently show that ST LMi was brightest in 1986 June and faintest in 1987 February.

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Table 1. Observing log, detailing starting point and duration of each run for each photometric band. Heliocentric Julian Date (HJD) is offset by 2440000.0 d.

<table>
<thead>
<tr>
<th>Band</th>
<th>Start</th>
<th>Phase</th>
<th>Duration (minutes)</th>
<th>Period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
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<td>0.764</td>
<td>67</td>
<td>0.58</td>
</tr>
<tr>
<td>$R_c$</td>
<td>6438.20641</td>
<td>0.764</td>
<td>67</td>
<td>0.58</td>
</tr>
<tr>
<td>$H$</td>
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<td>0.768</td>
<td>67</td>
<td>0.58</td>
</tr>
<tr>
<td>$B$</td>
<td>6439.16001</td>
<td>0.821</td>
<td>126</td>
<td>1.10</td>
</tr>
<tr>
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<td>0.821</td>
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<td>1.10</td>
</tr>
<tr>
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<td>0.821</td>
<td>161</td>
<td>1.40</td>
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<tr>
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<td>86</td>
<td>0.75</td>
</tr>
<tr>
<td>$H$</td>
<td>6610.83491</td>
<td>0.473</td>
<td>86</td>
<td>0.75</td>
</tr>
<tr>
<td>$B$</td>
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<td>0.333</td>
<td>85</td>
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<td>0.76</td>
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<tr>
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<tr>
<td>$J$</td>
<td>6852.05378</td>
<td>0.438</td>
<td>224</td>
<td>1.90</td>
</tr>
</tbody>
</table>
Figure 1. B-band photometry, linear polarization, position angle and circular polarization observations taken on 1986 January 8. Data are grouped into 0.02 $P_{\text{orb}}$ bins and repeated over two whole phases for clarity.

4 DISCUSSION

4.1 The primary accretion region

The position angle, $\theta$, of the linear polarization is most clearly defined in the $R_c$ band, and particularly during the bright phase where the linear polarization is strongest. This is to be expected since the $R_c$ band lies at the peak of the polarized flux distribution according to BWS (see Fig. 6 and later in this section). Also expected from BWS's flux distribution is the low polarization at $B$ where no overall pattern of position angle variation can be made out.

In the $R_c$ band, the position angle changes from $40^\circ \pm 20^\circ$ at $\phi_{\text{orb}} = 0.4$, through $180^\circ$ to $10^\circ \pm 2^\circ$ at the beginning of the bright phase ($\phi_{\text{orb}} = 0.7$). At the beginning and end of the...
bright phase there is a local maximum peak in the data; between these points, the rate of increase is less than earlier in the cycle. From the end of the bright phase to $\phi_{\text{orb}} = 0.4$ the polarization is too low for the position angle variations to be clearly defined.

We used the method of SSG to find the inclination of the system, $i$, and the colatitude, $\beta_1$, of the pole. The rate of change of the position angle, $\dot{\psi}$, in the mid-bright phase between $\phi_{\text{orb}} = 0.82$ and 0.94 was measured and combined with the duration of the bright phase, as determined by the linear polarization peaks. The resulting values $i = 66^\circ$, $\beta_1 = 147^\circ$ are broadly in line with those determined by SSG ($i = 69^\circ \pm 5^\circ$, $\beta_1 = 148^\circ \pm 2^\circ$) and MSC ($i = 56^\circ \pm 4^\circ$, $\beta_1 = 134^\circ \pm 4^\circ$), in which the size of the accretion region was

Figure 2. As for Fig. 1 but $R_2$-band data.
Figure 3. As for Fig. 1 but $I_c$-band data from 1987 February 25.

taken into account, but the lower accuracy of our linear polarization observations prevents us from improving on their calculations.

An interesting aspect of the position angle data is the flatter variation during the bright phase seen in the $I_c$-band observations of 1987 February 25 and the $R_c$-band observations of 1986 January 8. A likely explanation for this is that the centroid of emission is at higher magnetic latitudes in the $I_c$-band data since the inclination $i$ cannot change.

Since the primary accreting region is eclipsed by the white dwarf during the faint phase, we can obtain the emitted cyclotron flux, to first order, by subtracting the faint-phase flux from the bright-phase flux. The values obtained are shown in Fig. 6, along with those of BWS for comparison. Our data help to fill in the gap in spectral coverage between the $R_c$ and $J$ bands. Although our data were not all taken at the same epoch, they generally show significantly more flux in the near-infrared and a cyclotron turnover further to the
red than implied by BWS’s data. [It should be noted that faint phase contamination from the secondary accretion region in the infrared (see Section 4.2) means that the calculated cyclotron fluxes redwards of 1 μm may well be too low.] Wickramasinghe & Meggitt (1985b) found difficulty in applying their homogeneous, constant-temperature models to the combination of the steep optically thin spectrum in the blue and the flat turnover of BWS’s data. Our data obviate this problem but the main flaw in their fits remains the low predicted polarization in the red, although Wickramasinghe & Ferrario (1988) have shown that significant polarization can be produced at low harmonics for emitting regions of moderate to large extent. Wu & Channugam (1988) also used BWS’s data to fit a two-core model (see their fig. 8) which,
whilst using a lower temperature of 10 keV, is also in excellent agreement with our red observations. They did not produce corresponding polarization models.

The long photometric maximum in $B$ on January 8, which extends over a much larger phase range than the circular polarization peak, is puzzling. Although not present on other dates to such a pronounced degree, it can possibly be attributed to the reprocessing of radiation from the accretion region by the white dwarf photosphere over an area very much larger than the accretion region itself. An alternative possibility is that the extended blue emission could be attributed to the emission-line region of the accretion stream.

4.2 The secondary accretion region
That accretion takes place at the second pole is clearly evident from our $H$-band data, which show strong circular polarization up to between 15 and 20 per cent during the
Figure 6. Cyclotron total and polarized flux distributions for the primary emitting region with BWS's data given for comparison.

faint phase in the opposite sense to that seen in the bright phase in the $R_\text{c}$ band. Our $J$-band observations in February (Fig. 4) show negative polarization in the bright phase similar to the $R_\text{c}$ band up to about 7 per cent, but also show positive polarization in the faint phase with noisy peaks corresponding to those in $H$. There is no evidence for systematically positive circular polarization in the $I_\text{c}$ band (Fig. 3). Cyclotron emission from the second pole in ST LMi therefore takes place only at infrared wavelengths. This is very different from the situation in VV Pup, where cyclotron emission
from the second pole was observed in a broad, unfiltered band from 3200 to 8600 Å, or roughly from $U$ to $I_c$ bands by Liebert & Stockman (1979).

The $H$-band circular polarization (Fig. 5), shows a local minimum at $\phi_{\text{orb}} \approx 0.3$ which is probably due to cyclotron beaming effects, similar to those seen in the optical in V834 Cen (for example in Cropper, Menzies & Tapia 1986). The position of the primary minimum implies that the second accretion region is most nearly in the line of sight at $\phi_{\text{orb}} = 0.35 \pm 0.05$, assuming a centred dipole. There is also a narrow but clear minimum in the $J$-band circular polarization at $P_{\text{orb}} = 0.37$, again in agreement with the $H$-band polarimetry.

The absence of negative polarization in $H$ from the primary region during the bright phase may be due to cancellation by polarized flux from the secondary region. The mean circular polarization between $\phi_{\text{orb}} = 0.80$ and 0.95 is $0.7 \pm 0.6$ per cent, which is not significant. As it is unlikely that the cancellation would be exact, we conclude that there is probably no significant polarized radiation from the primary emitting region in the $H$ band. This confirms the conclusion reached by BWS.

We estimate the peak polarized cyclotron flux in $J$ and $H$ at $\phi_{\text{orb}} = 0.5$ to be $0.04 \pm 0.02$ mJy and $0.27 \pm 0.05$ mJy, respectively. If the $J$- and $H$-band polarized fluxes are emitted from the same region, the rising polarized flux with wavelength implies that it is optically thin. Furthermore, if the magnetic field is similar to that at the main accretion region, a relatively low column density (and thus accretion rate) is indicated. By comparing these two infrared polarized intensities with models of cyclotron emission, we can set some limits on the dimensionless depth parameter, $\Lambda < s_n / B$, in the emitting region where $s$ is the physical depth, $n_e$ the electron number density and $B$ the magnetic field (see for example Wickramasinghe 1984). We have used models similar to those of Meggitt & Wickramasinghe (1982) and Wickramasinghe & Meggitt (1985a) but with a much finer coverage of parameter space. Wickramasinghe & Meggitt (1985b) find a shock temperature of between 15 and 30 keV for the main emission region. Since we expect cyclotron cooling to be more dominant at the second pole, we can adopt this as an upper limit. Due to the large uncertainty in the $J$-band flux, only upper limits can be derived for $\Lambda$. At 20 keV a field as large as 30 MG is prohibited because the model cyclotron turnover is always too far to the blue. At 20 and 15 MG we find limits for $\Lambda$ of $\approx 10^4$ and $\approx 10^3$. At lower temperatures harmonic structure does not allow us to find accurate limits but at 10 keV, again, a 30-MG field is prohibited and we estimate that $\Lambda \approx 10^3$ for 20 and 15 MG. Both SSG and BWS found a mean field of $\sim 18$ MG from Zeeman splitting. Although SSG derived a polar field of $\sim 30$ MG from the Zeeman data, it should be noted that this assumes a cent$:$sec dipole field distribution.

Given that the inclination is already known, we can use the duration of visibility of the secondary emission region to determine its colatitude, $\beta_2$. Using a value of 0.85 $P_{\text{orb}}$ we obtain $\beta_2 \approx 30^\circ$. We calculate that the two emission regions subtend an angle of $\sim 170^\circ$ at the centre of the white dwarf and are thus close to diometric opposition. The fact that the accretion regions are not diametrically opposed may result entirely from their displacement from the magnetic poles but may also imply that the field geometry is not a centred dipole.

### 4.3 X-ray observations

The secondary emitting region is not seen in EXOSAT soft X-ray observations (Beuermann 1988) taken simultaneously with our 1986 January 8 data; the count rate was less than 1 per cent of that from the primary region. This is consistent with cyclotron-dominated emission resulting from a low accretion rate (Lamb & Masters 1979) and similar to VV Pup (Mason 1985). It does, however, contrast with some systems (e.g. AM Her, BL Hyi, QQ Vul) where there is strong X-ray emission from the secondary region but little or no optical cyclotron radiation. These latter objects provide strong evidence (see e.g. Beuermann 1988) for the existence of a 'lumpy' accretion where larger blobs of accreting material penetrate the field further before being threaded. Consequently large blobs may cross the magnetic equator and, if the accretion rate is sufficiently low, accrete on to the surface without forming a shock, thereby depositing their energy directly into the surface layers of the white dwarf where it will be radiated away as soft X-rays (Kuijpers & Pringle 1982). 'Lumpy' accretion does not, therefore, appear to take place at the secondary region of ST LMi. This is supported by the absence of any substantial flaring in our light curves.

### 5 CONCLUSIONS

The presence of positive circular polarization in the near-infrared faint-phase data of ST LMi clearly indicates that accretion occurs on to a second region on the white dwarf surface for this object. Furthermore, the polarized flux from the secondary region, which is located at phase $\approx 0.35$ and colatitude $\sim 30^\circ$, indicates a lower accretion rate than at the primary region.

AM Her systems are known to have variable behaviour and apparently variable geometries and the data presented here highlight the importance of full phase coverage, simultaneous optical and near-infrared observations and frequent monitoring. In particular we require further observations of ST LMi in the red and near-infrared to determine better the secondary emission region's spectrum and its location on the white dwarf.

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