Record circular polarization discovered in the shortest period magnetic cataclysmic variable, RE 1307 + 535

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ABSTRACT
We report the discovery of very strong, variable (+50 to −20 per cent) circular polarization in the ROSAT EUV source RE 1307 + 535 in the red (R band) spectral region. The amplitude and the peak value of the broad-band circular polarization are the largest observed so far in any astronomical object.

Key words: polarization – stars: individual: RE 1307 + 535 – stars: magnetic fields – novae, cataclysmic variables – ultraviolet: stars.

1 INTRODUCTION
RE 1307 + 535 was detected in the ROSAT Wide Field Camera (WFC) EUV survey, and subsequent optical spectroscopic and photometric observations showed that the object is most probably an AM Her system (Osborne et al. 1994). An AM Her system consists of a synchronously rotating, highly magnetic \(B \approx (3-4) \times 10^7\) G white dwarf accreting from a close, low-mass binary companion \((-0.1 M_\odot)\) filling its Roche lobe. The magnetic field of the white dwarf prevents the formation of an accretion disc, and the accretion flow follows the magnetic field lines on to the white dwarf instead. The infalling material \(V \approx 5000\) km s\(^{-1}\) is shocked close to the white dwarf surface, and optical and infrared cyclotron emission regions are formed near the magnetic pole(s). These emission regions (or areas close to the cyclotron regions) also radiate in both hard and soft X-rays (and the EUV). In their discovery paper, Osborne et al. (1994) determined the orbital period from photometry to be 79.69 min for RE 1307 + 535, which is the shortest found for an AM Her system. A lower limit to the distance of RE 1307 + 535 of \(d > 710\) pc was derived from infrared photometry (Osborne et al. 1994), indicating that it is probably a halo object with \(z > 630\) pc.

2 OBSERVATIONS
We carried out circular polarimetry of RE 1307 + 535 on the nights of 1994 February 4/5 and 5/6 at the Nordic 2.54-m Optical Telescope (NOT) on La Palma, with an imaging polarimeter consisting of a super-achromatic \(\lambda/4\) retarder and a plane-parallel calcite plate in front of the Tektronix 512 × 512 CCD detector. Fig. 1(a) gives the results from the R-band (600-710 nm) polarization measurements, folded over the 79.69-min orbital period using the ephemeris from Osborne et al. (1994).

The circular polarization reaches about +50 per cent (Fig. 1a), which makes RE 1307 + 535 the most strongly circularly polarized astronomical object so far detected. Other AM Her systems show a maximum polarization of <40 per cent. In addition, the 70 per cent amplitude of the variations for RE 1307 + 535 (+50 to −20 per cent) is almost a factor of 2 larger than observed in any other system. There is a reversal of the sign of the circular polarization from positive (right-handed) to negative (left-handed) values in the phase interval 0.3–0.6. This indicates that cyclotron emission takes place at two opposite magnetic poles.

The R-band light curve obtained during the polarization measurements is shown in Fig. 1(b). The object is brightest during the phase interval of positive circular polarization, with the minimum brightness coinciding with maximum negative circular polarization. The system was in a high accretion state during our measurements on 1994 February 4–6 (magnitude range \(R = 17.7–18.6\)). During the episodes of low mass transfer, the brightness may fall to \(R = 19.5–20.5\) (Osborne et al. 1994).

There is a broad dip in the bright part of the light curve at the circular polarization maximum (phase 0.0). We attribute this to a cyclotron beaming effect when the region of positive circular polarization is closest to face-on. Theoretically, the emission intensity is largest into directions perpendicular to the field lines, and decreases to zero along the field lines (Wickramasinghe & Meggitt 1985). Hence the observed brightness is reduced when we look most directly at the cyclotron region.

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The AM Her emission regions are also prominent soft X-ray and EUV sources ($kT \sim 10-40$ eV), a feature which has greatly helped in detecting new AM Her systems. The soft X-ray emission is optically thick, and thus depends on the projected area of the emission region. This implies that the soft X-ray brightness should be at its maximum when the emission region is closest to face-on. We have compared our results with the ROSAT WFC sky survey EUV light curve (Osborne et al. 1994), and found that the S1-filter (90–206 eV) light curve reaches maximum near phase 0.0, in agreement with our interpretation which predicts the active accretion region to be closest to face-on at this phase (0.0).

3 MODELLING

Earlier geometric model considerations (Osborne et al. 1994) for RE 1307 + 535 have been based only on light-
curve data in the optical and EUV, and have assigned the
deep intensity minimum (phase 0.5) to cyclotron beaming
effects arising when the accretion region is closest to face-on,
and the weaker minimum (phase 0.0) to possible occultation
of the emission region by the white dwarf body. Such a
geometry, however, has difficulties in explaining the phasing
of our circular polarization curve. This shows sign reversals
either side of the deeper intensity minimum, consistent with
the emission regions crossing the limb at these phases. Our
model associates the maximum in the EUV light curve with
the brighter cyclotron emission region, which has positive
circular polarization. This is closest to face-on at phase zero.

There is no dip in the circular polarization curve near
phase 0.0. Therefore the contributions from the unpolarized
background sources (the underlying stellar photosphere and
thermal emission from the circumstellar matter) must be
negligible compared to those from the cyclotron emission
regions, as they have no diluting effect in the observed
circular polarization. Outside the broad dip of the bright-
phase light curve, the shapes of the polarization and light
curves suggest that geometry (visibility of the emission
regions) dominates over physics (cyclotron beaming effects)
there. The high degree of polarization observed requires that
the observed R-band flux of RE 1307 + 535 be dominated
by cyclotron emission from a homogeneous region with little
spread in the field strength and direction. Relative contribu-
tions from unpolarized (thermal) radiation sources are
unusually small, which could be due to the lack of stream
emission.

In order to constrain the system geometry further, we have
computed simulated polarization and light curves (Fig. 2) for
a model containing two extended cyclotron emission regions
on the surface of the spinning white dwarf, seen at inclination
i (the angle between the line of sight and the spin axis). These
emission regions consist of a set of strips (five and two for the
positively and negatively polarized regions respectively: Fig.
3). Each strip in both of the regions was divided into 20
points, for which all four of the Stokes parameters (Q, U, V
and I) were calculated (Pirola, Coyle & Reiz 1990; Pirola
et al. 1993 a; Pirola, Hakala & Coyne 1993 b), taking the
viewing angle dependences of the degree of polarization and
the total flux from physical cyclotron models (Wickrama-

![Figure 2](image_url)

**Figure 2.** Polarization and intensity curves from a model with two extended, almost diametrically opposite, cyclotron emission regions at
colatitudes \( \beta_i = 30^\circ - 50^\circ \) and \( \beta_s = 130^\circ - 135^\circ \). The respective extents in longitude are \( 65^\circ \) and \( 35^\circ \). The inclination of the white dwarf spin axis is
\( i = 75^\circ \). Curves from top to bottom give the position angle and the degree of linear polarization, the degree of circular polarization and the total
intensity (on a magnitude scale). The slightly displaced curves in the left-hand panels correspond to individual emission strips separated by \( 5^\circ \) in
latitude (five strips for the positive and two strips for the negative circular polarization regions). The right-hand panels give the combined
curves from the two extended regions. The \( k T = 20 \) keV, \( \Lambda = 10^4 \), cyclotron model was applied. With a magnetic field strength \( B = 3 \times 10^7 \) G,
the R-band effective wavelength corresponds to the cyclotron harmonic \( n = \omega / \omega_c \sim 5 \), where \( \omega_c \) is the fundamental electron cyclotron
frequency.
We have simplified the calculations here by assuming that the field lines are radial, which is nearly the case if the emission region is not far from the magnetic pole. For distances $<25^\circ$, the field lines of a centred dipole deviate by $<13^\circ$ from the white dwarf normal.

We have obtained a good description of the data (continuous line in Fig. 1) using a model with $i=75^\circ$ and two extended emission regions at the colatitudes (angular distance from the rotational pole pointing closest to us) $\beta_1 = 30^\circ-50^\circ$ (positive circular polarization emission region) and $\beta_2 = 130^\circ-135^\circ$ (negative circular polarization emission region), and extended in longitude by $65^\circ$ and $35^\circ$, respectively (Fig. 3). We have adopted for these calculations a field strength $B=30$ MG (Osborne et al. 1994), which gives cyclotron harmonic number $n \sim 5$ for our red spectral passband ($600-710$ nm). We also show in Fig. 2 the linear polarization and position angle curves given by the model. Broad linear polarization pulses are predicted at the phases 0.3 and 0.7, where the magnetic field lines are nearly perpendicular to the line of sight.

4 DISCUSSION

The detection of such a highly variable circular polarization in RE $1307+535$ indicates that the fractional contribution of the cyclotron emission to the total optical emission is significantly higher than in any other AM Her system. There are two possible reasons. First, the cyclotron emission region may be more homogeneous in terms of magnetic field strength and direction. Secondly, the fraction of unpolarized light may be unusually small. In a short-period system like RE $1307+535$, the optical emission from the $\sim 0.1-M_\odot$ secondary is negligible, which might be one reason for a very low level of unpolarized radiation. Studies of other (eclipsing) AM Her systems, however, have revealed that the emission from the accretion stream can be a major contributor to the optical emission (Hakala et al. 1993; Bailey, private communication). This emission is likely to dilute the observed polarimetric variability in all AM Her systems.

It is possible that in RE $1307+535$ the stream emission is significantly fainter than in other AM Her stars. This might be due to the high ratio of the white dwarf magnetic field to the binary separation in this system (Osborne et al. 1994), resulting in an accretion stream geometry determined along most of its length by the magnetic field. In this case, the magnetic pressure would dominate over the stream ram pressure (Liebert & Stockman 1985; Hameury, King & Lasota 1986) all the way from the white dwarf to the Lagrangian L1 point. If we denote the radius from the white dwarf at which the accretion stream ram pressure equals the magnetic pressure by $R_{\text{mag}} (\sim 2.0 \times 10^{10}$ cm), and
assume a typical total mass of 0.7 M\(_{\odot}\) for the binary, we obtain \(2.4 \times 10^{10}\) cm for the distance from the L1 point to the white dwarf. This is comparable to \(R_{\text{mag}}\), which means that in the case of RE 1307 + 535 the stream might not be heated up because of turbulence or twisting of field lines at \(R_{\text{mag}}\), but instead might closely follow the magnetic field lines. The resulting low stream emission, together with the low luminosity of the secondary, might be the cause of the high polarimetric variability observed.

It is interesting to compare the properties of RE 1307 + 535 with those of EF Eri, which has a similarly short orbital period of 81 min. Unlike RE 1307 + 535, EF Eri shows only modest circular polarization variability. This is not too surprising, since the recent magnetic field estimates for EF Eri (Östreich et al. 1990) have suggested that its field strength is only 10 MG. In addition, two magnetic poles of different sign are seen simultaneously in this system, and thus reduction of the observed polarization is inevitable. The low magnetic field might also result in increased stream emission because of a reduction of \(R_{\text{mag}}\). The field strength of the white dwarf in RE 1307 + 535 is about 3.5 times the field strength in EF Eri, so \(R_{\text{mag}}\) would be a factor of 2 smaller in EF Eri (assuming similar white dwarf masses). Thus the accretion stream trajectory in EF Eri resembles the trajectories of the streams in the longer period, intermediate-field-strength polars, rather than that of RE 1307 + 535. In these cases, where the accretion stream is accelerated towards the white dwarf in the orbital plane before impacting the magnetosphere, the process of magnetic entrainment can be expected to result in heating of the accreting gas at \(R_{\text{mag}}\). In systems without such a horizontal stream, such as RE 1307 + 535, connection to the white dwarf's magnetic field may be quieter, resulting in less stream heating, and thus less stream emission.

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REFERENCES