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Polarimetry of QQ Vul

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ABSTRACT

This paper presents an investigation of the polarisation behaviour of the AM Her system QQ Vul at several epochs over 3 years. There are changes of a factor of 2 in the amplitude of the orbitally phased circular polarisation from epoch to epoch. The mean behaviour can be modelled with an accretion arc ahead of and closer to the orbital plane than the magnetic pole, but it has proven difficult to link the changes in polarisations with changes in the location of the accretion region. The paper concludes with an investigation into whether the variations are periodic, but the evidence for this is marginal.

Key words: binaries: close, stars: individual: QQ Vul, stars: magnetic fields, Cataclysmic Variables, X-rays: stars, accretion, polarization.

1 INTRODUCTION

QQ Vul (E2003+225) is a member of the AM Her class of Cataclysmic Variables. These are interacting binary systems with white dwarf primaries which have magnetic field strengths of $\sim 20 \times 10^6$ G (for reviews see Cropper 1990 and Warner 1995). In the pre-ROSAT era, QQ Vul was distinguished by having the longest known orbital period – 222 minutes (now fifth-longest). Because the primary star in these systems is locked into synchronous (or near-synchronous) rotation with the secondary by the strength of its magnetic field, and because the binary separation scales with the orbital period, QQ Vul might be expected to be near the limit of synchronism.

A number of investigations of QQ Vul have been published. These include the original discovery paper (Nousek et al 1984), and an important early quasi-simultaneous investigation of the overall energy balance of an AM Her system covering X-ray to optical wavelengths with sufficient energy resolution in the soft X-ray band to constrain the soft X-ray component (Osborne et al 1986). Osborne et al (1987) noted a substantial change in the EXOSAT LE light curves between 1985 June and September. A number of spectroscopic investigations are also available (Mukai et al 1986, McCarthy, Bowyer & Clarke, 1986, Voǐkhanskaya, 1986, Mukai & Charles, 1987). However, besides thesis chapters on QQ Vul in Cropper (1985b) and Schwope (1991), the only published polarization data for this system is the limited quantity in Nousek et al (1984), from which very preliminary values are known for the inclination and latitude of the magnetic pole. In addition, the orbital ephemeris has been the subject of some uncertainty. This investigation was undertaken in order to provide a larger and more represen-

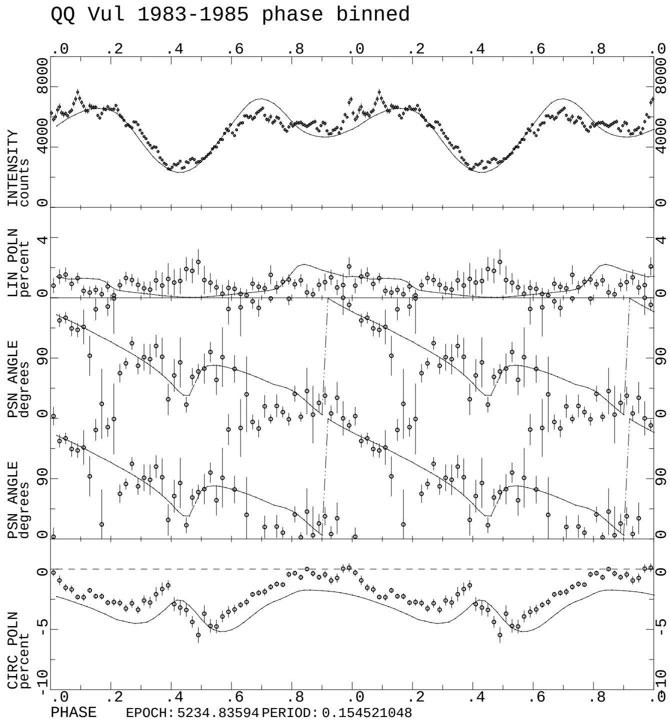

Figure 1. Mean phase-binned white-light polarisation of QQ Vul over the years 1983 to 1985 (Weeks 1 to 6). Model data is overplotted as a solid line (see text for details)

Run Number	Date	HJD start	Duration (min)	Telescope (m)	Week
MS002	83 Jul 15	5531.533	58	1.9	1
MS007	83 Jul 17	5533.434	180	1.9	1
S3200	83 Oct 6	5614.274	75	1.9	2
S3344	84 May 30	5851.505	248	0.75	3
S3348	84 Jun 1	5853.507	232	0.75	3
S3509	85 Apr 15	6171.622	43	1.0	4
S3516	85 Apr 25	6181.615	65	1.0	4
S3519	85 Apr 26	6182.592	91	1.0	4
S3530	85 Apr 29	6185.602	82	1.0	4
S3533	85 May 14	6200.569	140	1.0	5
S3536	85 May 15	6201.547	170	1.0	5
S3539	85 May 16	6202.542	170	1.0	5
S3545	85 May 17	6203.588	104	1.0	5
S3551	85 May 19	6205.545	101	1.0	5
S3586	85 Jun 19	6236.462	229	1.0	6
S3867	86 May 30	6581.538	206	1.0	7
S3869	86 May 31	6582.516	240	1.0	7
S3872	86 Jun 7	6589.562	166	1.9	8
S3875	86 Jun 9	6591.578	78	1.9	8

Table 1. Log of the photopolarimetric observations taken at SAAO. HJD's are 2440000.0+

tative body of polarization data from which these and other important parameters could be determined more reliably.

2 OBSERVATIONS

The polarimetric observations were made with the UCT Polarimeter (Cropper 1985a,b) in the simultaneous linear and circular polarimetry and photometry mode at the Sutherland site of the South African Astronomical Observatory. The 1.9, 1.0 and 0.75m telescopes were used for the runs which were taken over 4 years from July 1983 to June 1986. The observations have a total duration of 44 hours but most of the runs cover less than one orbit because of the northerly declination of the star. A white light bandpass (3200 − 9200Å) from a RCA31034A GaAs photomultiplier was used throughout. Integration times were 30, 60 or 120 seconds for the polarimetry and 2 or 5 seconds for the high speed photometry. A log of these observations is given in Table 1. They are grouped into weeks (week 4 includes a short run made ten days earlier).

The intensity data from individual weeks were scaled by the ratio of telescope aperture to that of the 1.0m. They were then folded on the orbital ephemeris (see section 3), averaged into phase bins and plotted as a function of phase. The mean curves for 1983 to 1985 (Weeks 1 to 6) are shown in Fig. 1. The binned curve is repeated over two phases for clarity and shows the light curve (on a linear scale) in the top panel, followed on the panels below by the linear polarization, its position angle, and the circular polarization at the bottom. The position angle is also plotted twice vertically for continuity.

Figure 2 shows the mean intensity (a) and circular polarization (b) data for each week.

3 THE EPHEMERIS

Nousek et al (1984) determined a period of 0.1545252 ± 0.0000003 day (222.52 min) from seven linear polarization peaks spanning 1515 cycles. Cropper (1985b) found that this period did not agree with polarimetry obtained at later epochs (runs MS007 to S3348 – Table 1) and proposed a quadratic ephemeris instead. Subsequent polarimetry (runs S3509 onwards) has shown that this ephemeris is also incorrect. Osborne et al (1986) obtained the unpublished linear polarization peak timings used in the Nousek et al (1984) investigation and included a timing from Cropper (1985b) to derive a linear ephemeris with a period of 0.1545217 ± 0.0000022 day, noting that the estimates of the timing errors had to be increased considerably in order to achieve a fit. It is clear even in the second panel of Fig. 11 in Nousek et al (1984) that the linear polarization peak is $0.05P_{orb}$ or 10 min later than predicted. This is appreciably greater than the uncertainty in the timing of the peak.

One of the problems of using the linear polarization peak to determine the period is its transitory nature. In the absence of any strong fiducial mark in the light curves and because the individual runs in Table 1 generally cover less than one orbital period, the method used to derive the period was to cross-correlate the weekly phase-averaged intensity data. The Week 5 data were used as a template because of their good signal to noise ratio and typical amplitudes for the orbital variation. Weeks 2, 4 and 8 were excluded because there are gaps in the phase-averaged data. Week 3 was excluded because the shape of the light curve was different from that of the template (the system was brighter at phase 0.8 than at phase 0.2) so that the cross-correlation yielded a spurious result. The average folded blue light curve given in Nousek et al (1984) Fig. 10 is also suitable for cross-correlation so that in total five averaged light curves were available for the analysis. Although this is only a few, each phase point in the cross-correlation results from the average of a large number of data points.

A good fit to a linear ephemeris was found to the light curve with a RMS scatter of less than 60 seconds. The derived ephemeris is:–

HJD	2445234.8361	E×0.15452105
±	4	6

This is the ephemeris supplied to Osborne et al (1987), except for a very small ($0.002P_{orb}$) adjustment to the epoch. Phase zero still refers to the peak of the linear polarization pulse (which occurred at the middle of the bright phase). All of the data presented in this investigation are phased relative to the above ephemeris.

This ephemeris is in agreement, within the errors, with that determined by Schwope (1991) (0.1545208d with an uncertainty of 5 in the last digit), but is slightly longer than that calculated by Andronov & Fuhrmann (1987) from archival plates and photoelectric photometry over a period of ∼ 50 years (0.15452036 with an uncertainty of 2 in the last digit). It is significantly shorter than the linear polarisation ephemeris in Nousek et al. (1984).

4 COMMENTS ON THE LIGHT AND POLARIZATION CURVES

The light curve in the total 1983-1985 dataset (Fig. 1) has a double-humped shape with unequal depth minima at orbital phase $\phi_{orb} \simeq 0.4$ and $\phi_{orb} \simeq 0.85$. The primary maximum occurs at $\phi_{orb} \simeq 0.1$. The circular polarization curve is roughly sinusoidal and negative. It reaches maximum negative values (∼ 5 per cent) at $\phi_{orb} \simeq 0.5$ and a maximum value of almost exactly zero at $\phi_{orb} \simeq 0.96$. The curve is deeply cut by a positive excursion to lower polarization values at $\phi_{orb} \simeq 0.35$. Another feature is a shoulder of negative-

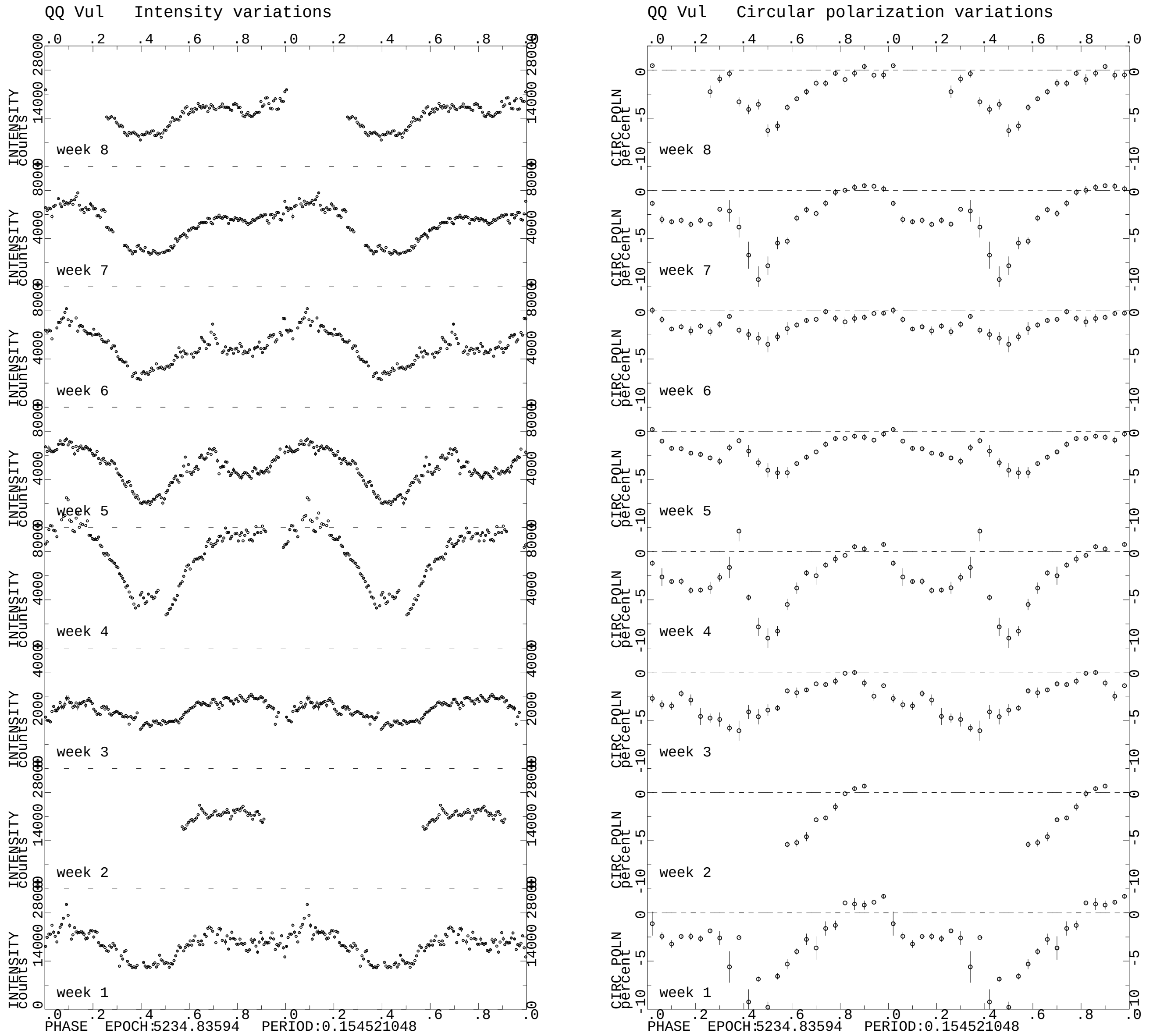

Figure 2. Phase-binned intensity (a) and circular polarisation (b) of QQ Vul week by week.

going polarization at $\phi_{orb} = 0.0$ (which is more obvious in, for example, the Week 7 data in Fig. 2).

The linear polarization is low throughout the orbit, never rising above ~ 2 per cent. A low peak is evident for $0.75 \lesssim \phi_{orb} \lesssim 0.1$. A wave-shaped position angle variation is present throughout the orbital cycle, even though the uncertainties are large for $\phi_{orb} \sim 0.2$ and ~ 0.6 because the measured linear polarizations are low.

There is clear evidence of a second linear polarization peak at $\phi_{orb} \simeq 0.5$. Despite the reduction in flux which naturally increases the linear polarisation uncertainties (and apparent level), this peak appears to be real. This is because the position angles at the phases of the second peak are generally well defined and consistent with the orbital variation.

The data in Fig. 1 are broadly similar to the I band data shown in Nousek et al (1984), (their fig. 11). There the linear polarization peak at $\phi_{orb} \simeq 0.0$ is more prominent, and the orbital behaviour of the position angle is not discernible. Their position angle measurement during the $\phi_{orb} = 0.0$ peak is similar to that shown in Fig. 1.

It is clear from Fig. 2 that the amplitude of the circular polarization orbital modulation varies from week to week. This is particularly evident in the 1985 data, where the amplitude of these modulations decreases progressively and markedly in the April, May and June observations (Weeks 4, 5 and 6). As the amplitude of the circular polarization variation decreases, the amplitude of the light curve decreases. Fig. 3 shows the data for those weeks (5, 6 and 8) in which the circular polarisation amplitude was ≤ 6.5 per cent (a),

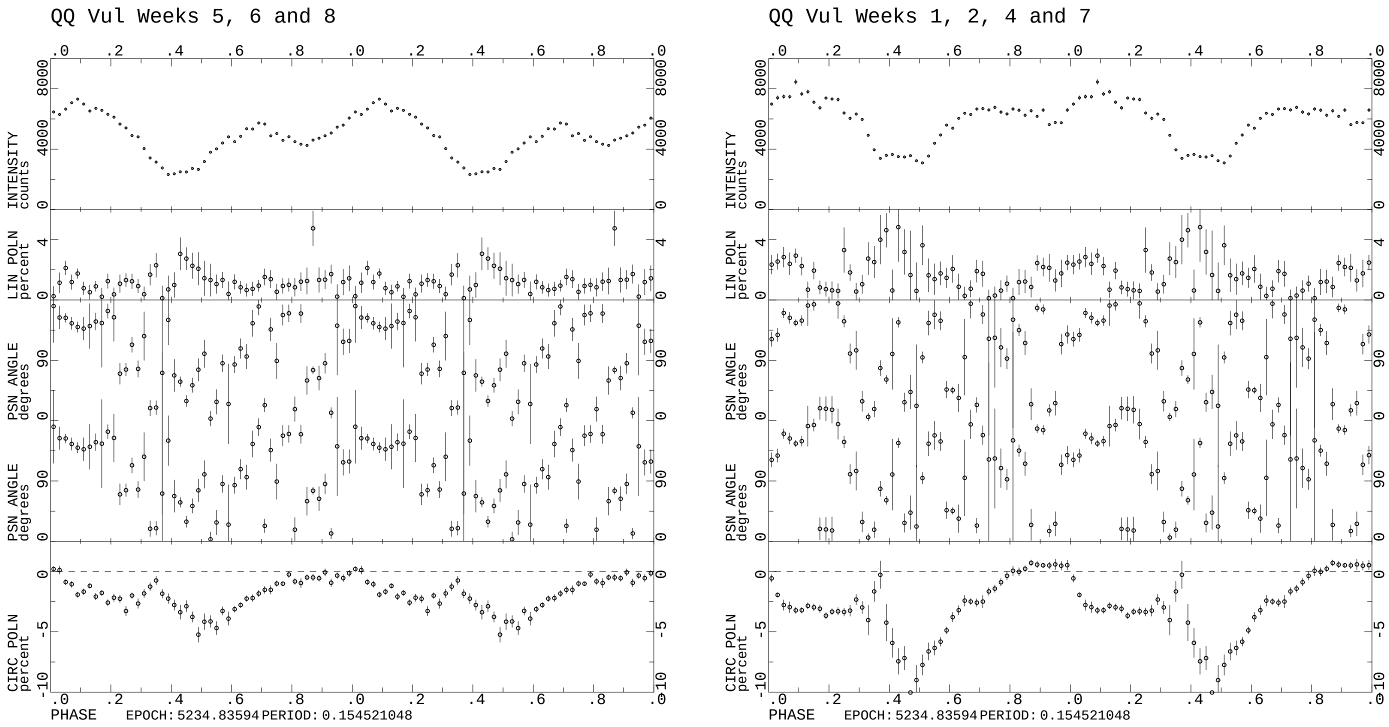

Figure 3. Phase-binned linear polarisation data for those weeks (5, 6 and 8) in which the circular polarisation amplitude was ≤ 6.5 per cent (a), and for those weeks (1, 2, 4 and 7) in which the circular polarisation amplitude was > 6.5 per cent (b).

and for those weeks (1, 2, 4 and 7) in which the circular polarisation amplitude was > 6.5 per cent (b).

5 CONSTRAINTS ON THE GEOMETRY

A prominent feature in the circular polarization curve is the drop to lower (absolute) levels of circular polarization at $\phi_{orb} \simeq 0.35$. This feature is caused by beaming of the cyclotron radiation and scattering of cyclotron flux by accreting material at those phases where the line of sight most closely approaches the axis of the column (Wickramasinghe and Meggitt 1985, Barrett & Chanmugam 1984). The indication is therefore that the cyclotron emission region is seen almost face-on at $\phi_{orb} \sim 0.5$. In the notation of Cropper (1989) in which ι is the inclination to the system and β the colatitude of the magnetic pole, then this requires $\iota - \beta \simeq 10°$. The circular polarisation drops to zero at $\phi_{orb} \sim 0.0$, occasionally becoming slightly positive, suggesting that it grazes the limb behind the rotation axis at this phase. Thus $\iota + \beta \simeq 90°$. The two equations yield approximate values for inclination and colatitude of $\iota \sim 50°$ and $\beta \sim 40°$. These arguments and conclusions are similar to those in Nousek et al (1984) and place QQ Vul in the category of "one-pole systems" in which only one accreting region is continually in view, as in V834 Cen (Cropper, Menzies & Tapia, 1986). The orbital intensity variations are caused by cyclotron beaming, with the orbital intensity minimum occurring when the emission region is most face-on. The closed wave-like position angle variation in Fig. 1 is another signature of one-pole systems, and its amplitude of $\sim 180°$ also indicates that the emitting region passes almost through the line of sight at $\phi_{orb} \sim 0.5$.

Although the broad features of the polarisation behaviour are clear there are a number of aspects which require a more detailed explanation. The fact that the cut in the circular polarisation does not occur at $\phi_{orb} \simeq 0.5$ when the circular polarization reaches its peak values can be explained as the result of a non-radial accretion flow. The positive excursions of the circular polarisations at $\phi_{orb} \sim 0.0$ also require the accreting field lines to have passed through the perpendicular to the line of sight, and yet remained on the visible hemisphere of the white dwarf. The degree of asymmetry in the circular polarisation is larger than in most AM Her systems and suggests that more careful modelling is required.

A single arc model assuming accretion along dipole field lines was therefore constructed, as in Potter et al (1997). A magnetic field of 30MG was assumed and the cyclotron flux in the white light bandpass was calculated from the Wickramasinghe & Meggitt (1985) 10 keV constant temperature model with $\Lambda = 10^5$. After a number of trials, the most successful model integrated the emission from spots running along a line in magnetic longitude and latitude from (210°,18°) to (265°,42°). The magnetic pole is at 0°and the longitude runs in the sense that 270°is ahead of the magnetic pole, so in white dwarf rotational coordinates this line translates to an arc below and ahead of the magnetic pole, with those points furthest ahead closer to the orbital plane. The value of ι was 40° and of β was 10°. This value for β is consistent with that deduced above (assuming radial accretion at the magnetic pole) when the displacement of the accretion region from the magnetic pole is taken into consideration (10° plus $\sim 30°$). Diluting (unpolarised) flux was added to approximate the contributions of the stellar photospheres and stream, and the polarisation fraction was also diluted by adding a constant fraction of the intensity as unpolarised flux. The resulting model is plotted as a solid line over the data in Fig. 1.

The shape of the polarisation curves is sensitive to the position and shape of the accretion arc. The generally more prominent rise in intensity after $\phi_{orb} = 0$ requires that the arc be located ahead of the magnetic pole, and the higher circular polarisation at $\phi_{orb} = 0.5$ compared to that at $\phi_{orb} = 0.3$ forces the arc to lower latitudes on its leading edge. As with other fits by eye to polarisation data, the model in Fig. 1 is not globally optimised: however, the data quality and the weekly variability make a full inversion of the data to determine the shape of the accretion region objectively (as in Potter, Hakala & Cropper 1997) inefficacious. Nevertheless, shape and position of the arc are as might be expected considering how the accretion flow might be threaded by the magnetic field.

Although not modelled in Fig. 1 the phasing of the second linear polarisation peak at ~ 0.5 requires that a second accretion region appears briefly at the edge of the limb at these phases – approximately at the footpoints of the closed field lines from the main region but slightly closer to the orbital plane. This is supported by the increase in 2–10 keV X-ray flux as measured by *Ginga* at this phase (Beardmore et al 1995). Most of the emission from this (perhaps larger) region may therefore always be hidden behind the limb of the white dwarf - a factor which should be taken into account in the calculation of bolometric luminosities.

6 THE LONG-TERM VARIATIONS

It is clear from Fig 2. that the amplitude of both the photometric and the circular polarization orbital modulation is different from week to week. At intervals spaced roughly by a month in April, May and June 1985 the amplitude of the circular polarization orbital modulation decreased from 9.1 to 4.3 to 3.5 per cent. In May 1986 the amplitude was 8.9 per cent and eight days later it had declined to 6.1 per cent. In this section an explanation is sought for these changes.

The measured polarization of the light emitted at the accretion region depends on a number of factors, such as the mass accretion rate, viewing geometry and the shape of the accretion region and its position relative to the magnetic field structure. These are interdependent.

Changes in mass accretion rate manifest themselves in AM Her systems most obviously by the existence of episodes reduced brightness (see for example the long record for QQ Vul in Andronov & Yavorskiĭ 1983). In the AM Her system HU Aqr, it has been found that a greater accretion rate causes part of the accretion stream to penetrate the magnetosphere more deeply than at lower accretion rates, before threading onto the field lines (Harrop-Allin et al, 1997). The "footprint" of these lines on the white dwarf is therefore at lower latitudes. If this is the case for QQ Vul, then the accretion region would be seen at a wider range of angles, thus producing larger amplitude circular polarisation curves.

No concurrent bolometric measurements are available for the system for each week, so it is not possible to relate the polarization changes directly to the mass transfer rate. White-light intensity measurements may give some indication as to the overall accretion rate, but the link between optical and bolometric luminosity is believed to be complex. Concrete evidence of this is available from Osborne et al (1987), where the V band intensity was highest when the *Exosat* 3000 Lexan counts were lowest. The white light measurements are therefore probably not useful, especially as no comparison stars were observed from week to week.

Changes to the model in Fig. 1 were made to see if changes to the location or shape of the accretion arc, or changes in β could reproduce the changes. This was inconclusive, in the sense that small perturbations of the parameters used in the model were unsuccessful, and complicated by the fact that the major changes are in amplitude rather than shape, and so can be mimiced by changing the dilution factors.

The mass transfer changes are clearly a possible mechanism for the polarisation changes, although in a sense they are not in themselves an explanation, merely moving the cause upstream to the source of the mass transfer changes, which itself is still unclear. On the other hand, one of the other possibilities noted above, changes of the viewing geometry may also be important. Geckeler & Staubert (1997) have recently made the important observation that for systems in which the magnetic axis is closer to the rotation axis than some critical value β_{crit} where $\tan\beta_{crit} = R_t/R_{wd}$ and R_t is the threading radius, then it is conceivable that it would *appear* that the white dwarf was locked into synchronous rotation without this actually being the case. The accretion stream threads onto successive magnetic field lines as the white dwarf rotates slowly with respect to the secondary, accreting at approximately the same location on the white dwarf along the locus of an ellipse. The only manifestations are small periodic changes in longitude and in the latitude of the accretion region. The former lead to changes in phase while the latter produce effects such as changes in the orbitally phased polarisation curves. The shape and extent of the ellipse depends on the dipole offset β: for those systems in which the dipole offset is aligned with the rotation axis, it is easy to appreciate that the ellipse is a circle around the rotation axis, and there are no phase shifts and polarisation changes, so that in this case there is no way to distinguish whether the white dwarf rotates synchronously. In the case of QQ Vul, the model in section 5 suggested that $\beta \simeq 10°$ and that the accretion arc was located ~ 30 degrees from the magnetic pole, implying a threading radius of $\sim 5R_{wd}$ and so $\beta_{crit} \sim 25°$. Thus for $\beta = 10°$ the Geckeler and Staubert condition is satisfied (and even for threading radii up to $\sim 30R_{wd}$), implying that there may be an amplitude swing of $\sim 20°$ in the angle at which we view the magnetic pole when closest to the line of sight. This could cause the change in the amplitude of the phased circular polarisation in Fig. 2.

Both the mass transfer rate and asynchronous rotation hypotheses would predict greater linear polarisation when the amplitude of the circular polarisation was greater. This is in fact as observed in Fig. 3 (a) and (b).

Because of the predictive nature of the asynchronous rotation hypothesis, we pursue it further below by investigating what other evidence there may be to support it.

6.1 A Search for Periodicities in the Polarizations

The asynchronous rotation hypothesis requires that the changes in the polarisations should be periodic. Unfortunately the circular polarisation measurements are available at only eight separate epochs (weeks 1 to 8). Schwope (1991) has kindly supplied the epochs of the data in his fig. 4.49, making 11 in total. Nousek et al (1984) do not state on which day the data from their fig. 11 is taken, mentioning only that polarization measurements were made centred on days 266, 286 and 348 of 1982. With so few data points it is almost impossible to explore the likelihood of periodic behaviour. However, a substantial observing campaign would be required to obtain a significant improvement over that available here, so the data were nevertheless tested to see if they were consistent with an underlying periodicity. The amplitudes of the phased circular polarisation in Fig 2 were measured (or estimated where the phase coverage is incomplete). Two amplitudes of ~ 9 per cent were measured 82 days apart (weeks 1 and 2). Any period in the data must be of this order or shorter than this. In addition, the decline to minimum circular polarization between Week 4 and 5 takes 20 days but the data are relatively unchanged within each week, so it is unlikely that the period is shorter than this.

A power spectrum of the 11 data points was computed and is shown together with the power spectral window in Fig. 4(a) and (b). As expected, none of the peaks is formally significant; however, we note that the maximum is at a period of 40.5 days, with an HJD epoch of maximum at 2445530.4 consistent with both the constraints noted above. The mean circular polarisation amplitude is 6.6 percent with an amplitude of the amplitude variation of 3.0 percent.

6.2 A Search for Peridicities in the Radial Velocities

QQ Vul is notable for having shown significant changes in the mean orbital radial velocities (γ velocities) (Osborne et al 1986) from epoch to epoch. A change in γ velocity would be possible under both hypotheses above. (Changes in the amplitude (k) of the radial velocities would probably be larger, but drawing conclusions from this is complicated by the line profiles which show broad bases and narrow peaks, the parameters of which are dependent on instrumental resolution from investigation to investigation.) The radial velocity γ values available in the literature are gathered together in Table 2. The γ velocities are not consistent with a variation on a 40.5 day period. They are remarkable in that observations after 1983 measured γ values of ~ 0 km s^{-1} whereas earlier observations had recorded both large positive and negative values. It is also difficult to reconcile the change in γ velocity of ~ 350 km s^{-1} in 1 orbital period reported in Osborne et al (1986) especially when the following orbital period shows no drifts in γ.

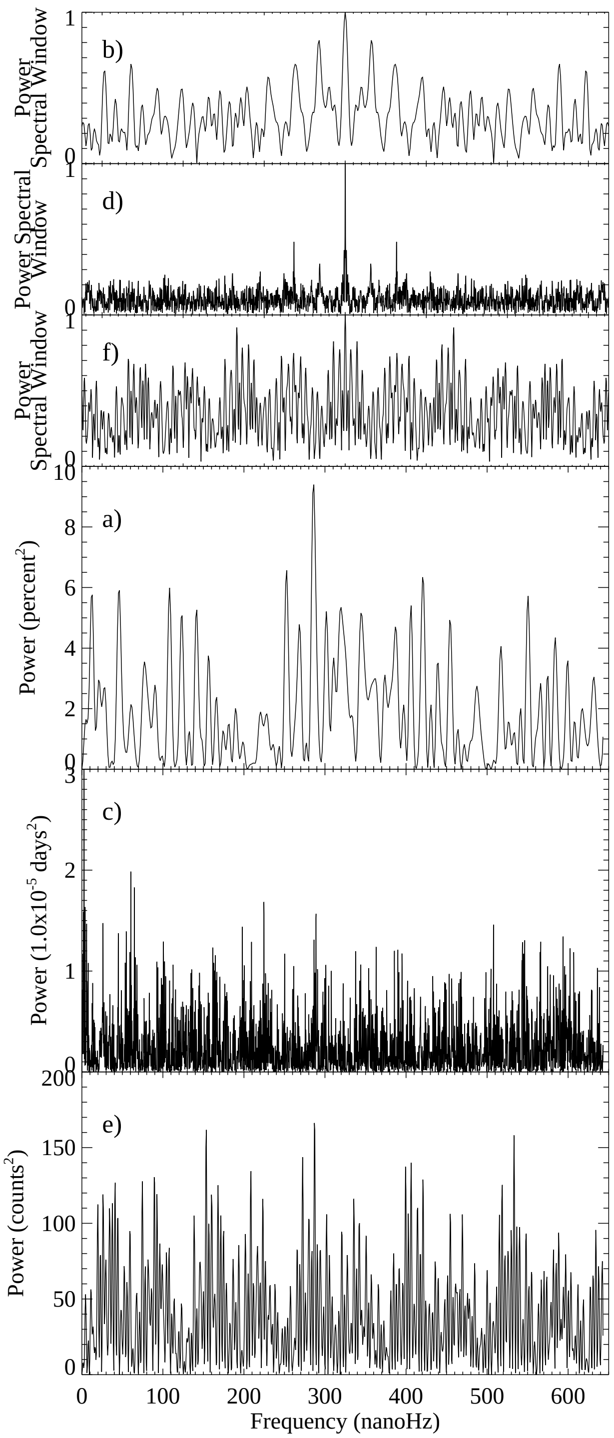

Figure 4. Power spectrum of the circular polarisation amplitude variation (a) with power spectral window (b). Power spectrum of the O–C residuals in Andronov & Fuhrmann (1987) (c) with power spectral window (d). Power spectrum of the X-ray countrate (in equivalent *Rosat* PSPC counts) at $\phi_{orb} = 0.6$.

Date	JD	$\Phi_{40.5}$	γ (km s^{-1})	Reference
1982 Aug 18	2445199	0.8	$+452 \pm 52$	Nousek et al (1984)
1983 Oct 12	2445619	0.2	~ 0	Osborne et al (1986)
1983 Oct 12	2445619	0.2	-343 ± 88	Osborne et al (1986)
1984 Jun 24	2445875	0.5	0 ± 30	McCarthy, Clarke & Bowyer (1986)
1984 Jul 3	2445884	0.7	$+20 \pm 20$	Voĭkhanskaya (1986)
1984 Jul 24	2445905	0.3	-11 ± 6	Mukai et al (1986)
1986 Jul 20	2446631	0.2	$+10 \pm 20$	Cropper (unpublished)

Table 2. The mean radial velocity variation γ against 40.5d phase ($\Phi_{40.5}$) from the literature.

6.3 A Search for Periodicity in the Long Term Light Curves

As noted above, a prediction of the Geckeler & Staubert (1997) asynchronous rotation model is that the shifts in accretion longitude cause periodic changes in phase. The longest time-series available to test for phase shifts is the timings of minima in the light curves given in Andronov & Fuhrman (1987) from plate archives. These stretch from 1934 to 1986. The deviations from the linear ephemeris in Andronov & Fuhrmann (1987) have been Fourier analysed as for Fig. 4(a) above and plotted on the same frequency scale in Fig 4(c). There are no significant peaks in the data. However, one of the highest peaks is at the 40.5 day period, and other high peaks are aliases from the window pattern.

The 40.5 day period is much shorter than that proposed by Andronov & Fuhrmann (1987) of 4282 ± 146 days from photometric observations. There is no particular evidence for such a period in Fig. 4(c).

6.4 A Search for Peridicities in X-rays

Osborne et al (1987) noted that the morphology of the *Exosat* Lexan 3000 X-ray light curves of QQ Vul changed substantially between 1985 June and September, to the extent that Osborne et al (1987) referred to the September data as a new soft X-ray mode. The most significant change is at $\phi_{orb} \sim 0.6$, at which time there is a deep minimum in the soft X-ray light curves in the 1983 October and 1985 June observations, but a maximum in the 1985 September light curves. These changes may be the result of a change in the range of viewing angles, so in order to investigate whether the soft X-ray light curves vary on the 40.5d period, the countrates at $\phi_{orb} = 0.6$ from these (converted using PIMMS to *Rosat* PSPC counts for a 25 eV blackbody spectrum with an absorbing column of 5×10^{19} cm $^{-2}$) were combined with those from the *Rosat* observations in Beardmore et al (1995) and phased. These are in Table 3. Additional short observations were extracted from the *Rosat* archive and reduced using ASTERIX (Saxton 1992) to produce light curves and phased on the orbital ephemeris in section 3. The counts at $\phi_{orb} \sim 0.6$ were measured and added to the published counts in Table 3.

As for the circular polarisation and long-term O-C variations, the counts Table 3 have been Fourier analysed and plotted on the same frequency scale in Fig 4(e). Again there are no significant peaks in the data. However, one of the highest peaks is at the 40.5 day period, and again other high peaks are aliases from the window pattern.

Date	c/s	Instrument	Reference
1983 Oct 12	2.1	*Exosat* LE	Osborne et al (1987)
1985 Jun 10	3.2	*Exosat* LE	Osborne et al (1987)
1985 Sep 14	21.2	*Exosat* LE	Osborne et al (1987)
1991 Apr 10	8.0	*Rosat* PSPC	Beardmore et al (1995)
1991 Apr 19	3.0	*Rosat* PSPC	Beardmore et al (1995)
1995 Apr 23	20.3	*Rosat* HRI	archive
1995 Apr 24	20.2	*Rosat* HRI	archive
1995 Oct 13	8.5	*Rosat* HRI	archive
1995 Oct 26	1.7	*Rosat* HRI	archive

Table 3. Soft X-ray count rates at $\phi_{orb} = 0.6$ (converted to *Rosat* PSPC-equivalent counts) from the literature or *Rosat* archive.

7 CONCLUSIONS

This investigation has followed the polarisation behaviour of QQ Vul over a period of years. From the average behaviour, a model can be constructed to explain the observations. This requires an elongated accretion region ahead of and below the magnetic pole. The threading radius implied by the distance of the region from the magnetic pole is small – $\sim 5R_{wd}$ especially by comparison with the large binary separation in this long-period system. The model fit requires the magnetic axis to be closely aligned to the spin axis of the white dwarf, so that in this system, Geckeler & Staubert's criterion that the spin axis is within the accretion ellipse is satisfied, and therefore that the observable effects of asynchronous rotation of the white dwarf may be small.

In each of Fig. 4(a), (c) and (e) there is a peak at the 40.5 day period, and in each case other high peaks are attributable to aliases. Unfortunately the significance level of the peaks means that the evidence for a variation at this period is inconclusive. Nevertheless, the evidence is sufficiently tantalising to contemplate the implication that the white dwarf rotates asynchronously in the system, with a period (synodic period) of 40.5 days. This is similar to the synodic periods in the three slightly shorter-period AM Her systems V1500 Cyg (7.9d, Schmidt, Stockman & Lamb 1988), RXJ1940.1–1025 (50.0d, Staubert et al 1994) and BY Cam (14.4d, eg Mason et al 1997). If QQ Vul is indeed not locked into synchronous rotation, then this suggests a reassessment of the extent to which other long-period AM Her systems are synchronised. Harrop-Allin et al (1997) have shown that using the criterion of Warner (1995), the longest period system RXJ0515+0105 can be expected to be synchronised, but this needs more detailed examination. The other long-period systems VY For (EXO032857–2606), RXJ1313–32 and RXJ0203+29 have not been investigated sufficiently.

Without further modelling of the position of the accretion region as a function of spin phase, it has proven difficult to connect this with the polarisation changes. Given its marginal evidence, this will have to depend on a confirmation of any periodicity. However, if this can ultimately be done it will be increase our understanding of the way in which the stream couples onto the field in these systems.

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