EVIDENCE FOR SUPERHUMPS IN THE RADIO LIGHT CURVE OF ALGOL AND A NEW MODEL FOR MAGNETIC ACTIVITY IN ALGOL SYSTEMS

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ABSTRACT

Extensive radio data of two Algol systems and two RS CVn binaries were re-analyzed. We found evidence for a new periodicity that we interpret as a superhump in $\beta$ Per~Algol, in which it may have been expected according to its semi-detached nature and low binary mass ratio. The concluded presence of an accretion disk (or an annulus) is consistent with previous studies of optical data and numerical simulations of $\beta$ Per. In our model, the 50-d period, previously found in the radio data of $\beta$ Per, is explained as the apsidal precession of the elliptical accretion disk / annulus. If our interpretation is correct, this is the first detection of the superhump phenomenon in the radio and the first observation of superhumps in Algol systems. According to our result, the accretion disk / annulus in $\beta$ Per precesses in spite of its non-Keplerian nature and therefore this phenomenon is not restricted to the classical Keplerian accretion disks in compact binaries.

We propose that in Algol systems with short orbital periods, which have accretion disks / annuli, the disk is magnetically active as well as the cool secondary star. The magnetic field in the disk originates from amplification of the seed field in the magnetized material transferred from the secondary. The disk and stellar fields interact with each other, with reconnection of the field lines causing flares and particle acceleration. Relativistic particles are trapped in the field and directed toward the polar regions of the secondary star because of the dipole structure of its magnetic field. These systems are, therefore, somewhat analogous to the RS CVn systems, which have two magnetically interacting stars. Our proposed model for the magnetic activity in Algol systems provides a simple explanation to the observed properties of $\beta$ Per in the radio wavelengths, and in particular, to the presence of quiescent gyrosynchrotron emission near the polar region of the secondary star, where electrons are difficult to be confined if the field lines are open as in normal single magnetic stars. It further explains the recent discovery that the Doppler shifts of the emission lines in the X-ray data of $\beta$ Per are somewhat lower than what is expected from the orbital motion of the secondary star. We propose that the superhump variation in the radio is generated by enhanced reconnection when the elongated side of the elliptic accretion disk is the closest to the cool star. This leads to flares and enhancement in particle acceleration and is manifested as stronger gyrosynchrotron radiation.

The observed superhump period, at $3.037\pm0.013$ d, ~6\% longer than the orbital period, was used to deduce a binary mass ratio of $\sim0.23$ in $\beta$ Per, which is consistent with previous studies. Our finding opens the possibility to extend the superhump phenomenon to Algol systems and to test the theories of precessing accretion disks in various types of interacting binaries. It provides a new method to estimate the mass ratios in these binaries. It also offers new insights and improves our understanding of the complicated magnetic interaction and feedback between mass transfer dynamics, time-dependent disk accretion, and feedback and induced magnetic activity in the Algols and related systems.

\textit{Subject headings: stars: accretion, accretion disks—binaries: close—radio continuum: stars—stars: flare—stars: magnetic fields—stars: individual (Algol)}

1. INTRODUCTION

In semi-detached systems, one star fills its Roche-Lobe and transfers mass to the other. There are several different groups of interacting binaries that are classified according to the properties of their component stars. In cataclysmic variables (CVs), a white dwarf accretes mass from a red dwarf (Warner 1995). In low mass X-ray binaries (LMXBs), the mass-receiver star is a black hole or a neutron star and the donor is typically a low mass solar-like star (Lewin et al. 1995). Algol systems contain a hot main-sequence star and a cool subgiant or giant companion (e.g., Peters & Polidan 1984). The mass transfer in interacting binaries is usually sustained through an accretion disk which is formed around the mass-receiver star. In CVs and LMXBs very often the disk is the dominant light source in the optical regime.

Many CVs show in their optical light curves quasi-periodicities a few percent different than the orbital periods (Warner 1995; Patterson 1999; Retter & Naylor 2000; Patterson et al. 2003). For historical reasons, these periods are known as superhumps. These humps were initially observed in the bright outbursts (superoutbursts) of SU UMa systems, a subclass of dwarf novae, which are a subgroup of CVs. O’Donoghue & Charles (1996) tested and confirmed the optical detections of superhumps in three LMXBs. Haswell et al. (2001) suggested that many more LMXBs share this property. There is, however, only one clear detection (in the LMXB V1405 Aql=X1916-
053) of superhumps in the X-ray regime (Retter et al. 2002). When the superhump periods are longer than the orbital periods, they are termed ‘positive superhumps’. Similarly, periods shorter than the orbital periods are called ‘negative superhumps’. Hereafter, we refer to superhumps as positive superhumps, which are the more common phenomenon. The superhump is understood as the beat periodicity between the orbital period and the apsidal precession of an elliptical accretion disk (Osaki 1985; Whitehurst 1988). It is argued that superhumps can only occur in systems with small mass ratios: $M_{\text{donor}}/M_{\text{receiver}} \leq 0.33$ (Whitehurst & King 1991; Murray 2000), although Retter et al. (2003) raised some questions about this limit by finding superhumps in TV Col, a CV with a relatively large orbital period, which probably implies a mass ratio above the theoretical limit.

Algol systems are named after the prototype Algol ($\beta$ Per) and may be progenitors of CVs (Iben & Tutukov 1985). Algol binaries typically contain a hot B–A main-sequence star and a cool F–K subgiant or giant which show a substantial magnetic activity (e.g., Peters & Polidan 1984; Richards et al. 2003). As in CVs and LMXBs, the mass transfer in the Algol systems with orbital periods longer than about 5 days is sustained through an accretion disk. In systems with shorter periods the disk may be transient, and in some cases it does not follow the Keplerian velocity field ($v \propto r^{-1/2}$) as in compact binaries, so it was termed ‘an annulus’ (Peters & Polidan 1984; Richards 1992, 1993; Richards & Albright 1999). Hydrodynamic simulations demonstrate that the mass transfer in the Algol binaries can indeed result in the formation of an accretion disk, a transient disk or an annulus around the mass-receiver star (Blondin et al. 1995; Richards & Ratliff 1998) and Doppler tomography supports this suggestion (Richards et al. 1995, 1996). We note that the numerical simulations show that the accretion material around a $\beta$ Per-type system can develop an asymmetrical structure that looks elliptical in shape (e.g., see fig. 1 of Blondin et al. 1995).

Eccentric accretion disks may, therefore, be expected in Algol systems whose mass ratios are below the critical value as well. However, in these objects the contribution of the disk in the optical band is very weak compared with the bright binary stars (Richards 1992). Thus, to look for superhumps it may be preferred to study other wavebands where the disk may have a larger impact on the light curve. The radio regime may, therefore, offers an opportunity to search for superhumps in Algol binaries.

In this work, extensive radio observations presented by Richards et al. (2003) were re-analyzed. The data cover four binary systems, two of which are Algol systems, and the other two belong to the RS CVn class. The RS CVn systems consist of two detached magnetically active stars, and thus should not have an accretion disk nor superhumps. The mass ratios of the Algol systems studied, $\beta$ Per and $\delta$ Lib, are 0.22 and 0.35 respectively (Richards et al. 2003). Therefore, $\beta$ Per has a mass ratio well below the theoretical limit of 0.33 and it should be the only system among the four that may show superhumps, although the mass ratio of $\delta$ Lib is just above the critical limit.

$\beta$ Per (Algol, HD 19356) at $V=2.1-3.4$ and $d=28.76$ pc is the brightest eclipsing system and the brightest and closest semidetached binary (Lacy 1979; Martin & Mignard 1998; Richards & Albright 1999; Richards et al. 2003). It has strong emission across the wavelength spectrum including the X-ray, ultraviolet, optical, infrared and radio (e.g., Lestrade et al. 1988; Richards 1990; Stern et al. 1995; Ness et al. 2002; Richards et al. 2003; Schmitt et al. 2003). $\beta$ Per is actually a hierarchical triple system with a B8 V main-sequence star, a K2 IV subgiant companion and a binary orbital period of 2.8673 days. The tertiary, which is an F1 IV star, orbits around the binary system with a period of 680.08 days (Hill et al. 1971; Richards et al. 1988; Richards 1992, 1993; Richards et al. 2003). The binary mass ratio of $\beta$ Per was estimated as 0.217±0.005 (Hill et al. 1971; Tomkin & Lambert 1978) and 0.22±0.03 (Richards et al. 1988). These values locate the system well inside the permitted range for superhumps, which would be predicted to be about 4–8% longer than the orbital period (Osaki 1985; Whitehurst 1994; Murray 2000). In this work, we present evidence for such a signal.

2. ANALYSIS

The radio observations were made between 1995 January and 2000 October using the NRAO-Green Bank Interferometer (GBI). The data were collected simultaneously in two bands (2.25 and 8.3 GHz). Two Algol systems ($\beta$ Per and $\delta$ Lib) and two RS CVn systems (V711 Tau and UX Ari) were observed. The initial analysis was done by Richards et al. (2003). A careful inspection of the power spectrum of $\beta$ Per (their fig. 29b) suggests that this system may have a photometric periodicity several percent longer than the orbital period. In addition, the power spectrum of $\beta$ Per is very different from those of the other three objects that typically show a strong signal at the orbital period. The new peak in the power spectrum of $\beta$ Per would be naturally interpreted as a superhump period. In this work, we highlight this finding, check the significance of this signal and show that it is indeed real.

The radio observations of $\beta$ Per contain 7442 measurements in each of the two frequency bands. This object is a strong radio source with frequent flares that reach above 1 Jy in the 8.3-GHz band (Richards et al. 2003). Figure 1 displays the power spectra (Scargle 1982) of the radio data of $\beta$ Per in the two bands. In the bottom panel (8.3-GHz) the highest peak in the frequency interval 0.1–0.9 day$^{-1}$ (only the range 0.1–0.8 day$^{-1}$ is plotted for presentation reasons) is at 0.3292±0.0013 day$^{-1}$. The corresponding periodicity, 3.037±0.013 d, is about 6 percent longer than the binary orbital period (2.8673 d). The orbital frequency of $\beta$ Per, marked by an arrow in the graph does not rise above the noise level. The 0.33-day$^{-1}$ peak is also seen in the 2.25-GHz band (Fig. 1, top panel) at a power similar to a blend of peaks around the orbital period. The strong peak at lower frequencies is the $\sim$50-d period (∼0.02 day$^{-1}$) discovered by Richards et al. (2003). There is also evidence for a signal about twice larger than the 0.33-day$^{-1}$ peak and for the beat between the 1-day$^{-1}$ alias and the 0.33-day$^{-1}$ peak. It is noted that the power spectrum of the 2.25-GHz band (Fig. 1, top panel) is very similar to that of the 8.3-GHz data (Fig. 1, bottom panel), but somewhat noisier. This is a simple consequence of the fact that the radio emission in the 8.3-GHz band is stronger. In addition, Richards et al. (2003) argued that the 8.3-GHz data represent the mean flux more reliably than the 2.25-GHz band.

The 3.037-d candidate periodicity does not appear in the window function. The significance of this peak in the 8.3-GHz data was checked by several methods. First, it was assumed that there are no periodic signals in the light curve. The data-points were randomly shuffled and power spectra for 100 simulated light curves were computed. The highest peak in these synthetic power spectra in the frequency interval 0.1–0.9 day$^{-1}$
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FIG. 1.—Power spectra of the radio data of β Per. Top panel: 2.25-GHz band. Bottom panel: 8.3-GHz data. Note that the radio emission in the 8.3-GHz band is stronger than the 2.25-GHz data and that the 8.3-GHz data better represent the mean flux (Richards et al. 2003). Both plots show a low-frequency at about 0.02 day\(^{-1}\). In the 8.3-GHz band, the highest peak in the interval 0.1–0.8 day\(^{-1}\) is at the frequency \(f_{\text{sh}}=0.3292\) day\(^{-1}\) (which corresponds to a period of 3.037±0.013 d). The location of the orbital frequency (which is marked by \(f_{\text{orb}}\)) is also shown. The arrows in the right-hand side of the diagram mark the second harmonic of the 0.3292-day\(^{-1}\) peak and its beat frequency with the 1-day\(^{-1}\) alias.

reached a power of 11, much lower than the value of \(\sim 30\) of the 0.33-day\(^{-1}\) peak in the raw data. The frequency range 0–0.1 day\(^{-1}\) was rejected because the noise sharply rises towards lower frequencies and similarly the frequency range near the strong 1-day\(^{-1}\) alias (0.9–1.0 day\(^{-1}\)) was avoided. Then, the significance of the suspected periodicity was checked in the presence of the 0.02-day\(^{-1}\) peak. A sinusoidal variation at this frequency was fitted and subtracted from the data. The residuals, assumed white noise, were shuffled and added to the sinusoid at the 0.02-day\(^{-1}\) frequency with the same amplitude it has in the data. In 100 simulations, the largest peak in the frequency interval 0.1–0.9 day\(^{-1}\) reached a power of 12.6, still well below the height of the proposed periodicity. In another test, it was assumed that the data are modulated with the orbital period as well. The significance of the 0.33-day\(^{-1}\) peak was similarly checked in the presence of this and the 0.02-day\(^{-1}\) frequencies. Again, the highest peaks in the frequency interval 0.1–0.9 day\(^{-1}\) in each power spectrum of the 100 simulations were well below the observed value. The strongest peak had a power of 13.0 with a standard deviation of 1.5, suggesting a very high significance level for the candidate periodicity.

In a different test, we estimated the probability of getting a signal inside the frequency range adequate for superhumps, which would be the strongest peak in the interval 0.1–0.9 day\(^{-1}\). The mass ratio of β Per implies that a positive superhump (if it exists) should be \(\sim 4–8\%\) larger than the orbital period (see previous section) and a negative superhump, \(\sim 2–4\%\) shorter (Patterson 1999; Retter et al. 2003). This implies that that the periodicity found in the light curve of β Per is significant at a level of about 97.4% (1–\(f_{\text{orb}}\times(\delta\epsilon_+ + \delta\epsilon_-)/\delta f=1–0.34876 \times (0.04 + 0.02)/(0.9 – 0.1) = 0.974\), where \(f_{\text{orb}}\) is the orbital frequency, \(\delta\epsilon_+\) and \(\delta\epsilon_-\) are the permitted ranges of the positive and negative superhumps respectively and \(\delta f\) is the frequency range we examined). The actual significance level is even higher if we consider the fact that a similar periodicity was not found in the light curves of the other three systems we investigated.

As a final check, the data were divided into two equal sections. The first part contained the early points and the second had the later datapoints. The candidate periodicity appeared in the power spectra of both parts (Fig. 2).

In the power spectrum, the second strongest peak after the 0.33-day\(^{-1}\) frequency is at \(\sim 0.21\) day\(^{-1}\) but it is only present in the 8.3-GHz data (Fig. 1, bottom panel). Since the noise level sharply rises towards low frequencies, it is much less significant than the 0.33-day\(^{-1}\) frequency. In addition, the fact that it does not appear in the two wavelength bands (Fig. 1) nor in both parts of the data (Fig. 2) suggests that it is not significant and should be ignored.

We also compared the quiescent data with the flaring observations. The radio data of β Per in the 8.3-GHz band were divided into two sections. The first part contained the faintest half of the points (representing the ‘quiescent’ data) and the second – the brightest measurements (the ‘flares’). The amplitude cutoff was about 20 mJy. The power spectrum of the flares clearly shows the 3-d period, which is absent from the power spectrum of the quiescent data (Fig. 3).

Figure 4 presents the mean shape of the 3.037-d period in the ‘flaring’ part of the 8.3-GHz data. The peak-to-peak amplitude of the variation is about 0.04 Jy. We have also analyzed visual photometry of β Per accumulated by the VSNET (Variable Star Network). These data contain 2517 points obtained during the past 95 years. No evidence for the 0.33-day\(^{-1}\) period was found. This result is not surprising since the B star overwhelms the light of the binary at these wavelengths.

3. DISCUSSION

In this work, radio data from four interacting binary systems were re-analyzed. We found evidence for superhumps in the light curve of β Per whose mass ratio obeys the theoretical condition for superhumps. In the data of the other three systems, we could not find any significant signals at the expected values (neither near the frequencies calculated from the theory using the mass ratios nor around the beat periods between the binary orbital periods and the long-term periodicities). This is as expected because the RS CVn systems (V711 Tau and UX Ari) are detached binaries (and thus are not expected to possess accretion disks at all) and since the mass ratio of δ Lib is slightly above the permitted values (Section 1). It is noted that the highest peak around the orbital period in the power spectra of V711 Tau and UX Ari is the orbital period itself (Richards et al. 2003), very different than in β Per. The power spectrum of
Fig. 2.— Power spectra of two equal sections of the 8.3-GHz data of \(\beta\) Per. Top panel: first 3721 datapoints. Bottom panel: second part (last 3721 measurements). The candidate periodicity \((f_{sh} \approx 0.33\,\text{day}^{-1})\) appears in both sections and is the strongest peak in the interval 0.1–0.8 day\(^{-1}\).

Fig. 3.— Power spectra of the 8.3-GHz observations. Top panel: the 3721 brightest datapoints (representing the ‘flaring’ data). Bottom panel: the 3721 measurements below about 20 mJy (the ‘quiescent’ data). The 0.33 day\(^{-1}\) period \((f_{sh})\) is seen in the flaring data, but not in quiescence.

Fig. 4.— The 8.3-GHz brightest datapoints (representing the ‘flares’ data) folded on the 3.037-d periodicity and binned into 20 equal intervals. Two cycles are shown for clarity. The dashed curve displays the sinusoidal fit to the data.
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The mass-gainer primary in Algol is a late B star whose envelope is radiative. The radio emission in Algol systems has thus been ascribed to the cool subgiant companion star, which, in contrast, has a thick convective envelope where dynamo processes could operate efficiently to produce magnetic activity (Favata et al. 2000). At a first glance, it is puzzling that the observed 3-d periodicity in the radio light curve of β Per, if it is a superhump phenomenon as those occur in optical and X-ray bands in CVs, is caused by an accretion disk or an annulus around the mass-receiver star.

Here, we propose a scenario to explain the radio properties of Algol systems with an accretion disk, and in particular, for the short period system β Per. It should be noted that for the Algol systems with orbital periods shorter than about 5 days, the disk may be transient, and unlike accretion disks in compact binaries, the velocities within this circumstellar structure around the primary star could become sub-Keplerian. This form of accretion disk / annulus (Richards & Albright 1999; Vesper et al. 2001), the velocities within this circumstellar structure around the primary star could become sub-Keplerian. This form of accretion disk / annulus, if present, could result in the formation of a permanent or transient accretion disk around the primary star (Blondin et al. 1995; Richards & Ratliff 1998). This accretion ring/annulus is dense and the flow is subsonic. Recent observations show evidence of such a ring/annulus (Richards & Albright 1999; Vesper et al. 2001), supporting the results of the numerical simulations and the interpretation of the optical data.

We argue that the accretion disk / annulus is magnetically active. Given that the secondary star has a significant magnetic field, the material transferred to the primary star is threaded by magnetic field lines. As the ram pressure of the accretion flow is larger than the magnetic stress at the Lagrangian point, the ionized accreting material drags the field along. Through the accretion disk / annulus, the field lines are wound around the mass-receiver star. The field is thus stretched and amplified, and at some stage reconnection can occur, causing flaring and acceleration of particles. These relativistic particles are trapped by the magnetic field of the secondary star and are focused onto the polar region by the dipole field. The radio emission is thus greatly enhanced in the polar region and becomes detectable in the radio image of the system. In spite of the field reconnection in the accretion disk / annulus, the lack of radio emission near the B star could be explained by the Razin effect and / or


\[ \delta \text{Lib is very noisy as its coverage is shorter than the other three objects and since its radio emission is much weaker than the other systems (Richards et al. 2003). Therefore, superhumps could be present in its data, but with an amplitude below the detection limit.} \]

The power spectrum of \( \beta \text{ Per} \) shows a periodic signal at 3.037 d, about 6% longer than the 2.867-d orbital period. This periodicity is located exactly at the beat period between the 50-d period (0.02 day\(^{-1}\)) and the orbital period. The tests given in the previous section show that it is unlikely caused by chance. Thus, we conclude that the phenomenon is real.

One may argue that the presence of the short orbital period and a long-term period may result in some physical change in luminosity that would be responsible to the presence of the beat periodicity in the power spectrum. However, there is only a weak evidence for the presence of the orbital period in the radio data of \( \beta \text{ Per} \) (Figs. 1–3). In addition, in the power spectra of the other three objects studied in this work there are no significant signals at the beat periodicities between their orbital and the long-term periods (Richards et al. 2003). These facts indicate that the radio light curve of \( \beta \text{ Per} \) is somewhat different than those of the other three systems.

If \( \beta \text{ Per} \) has superhumps they should be about 4–8% longer than the orbital period (Section 1). The 3.037-d period is at the middle of this range. The interpretation of the 3.037-d period as a superhump period is tempting. This would mean that the 50-d periodicity represents the apsidal precession period of the eccentric accretion disk. We note that an extended accretion disk is not required for the formation of superhumps. Superhumps have also been found in intermediate polars. In this subclass of CVs it is believed that the moderate magnetic field of the white dwarf truncates the inner part of the disk (e.g., Retter et al. 2003, and references therein). In the following, we adopt this interpretation of the data.

3.1. The mechanism of the radio superhump and the magnetic activity in Algol systems

The cause of the observed superhump variation in the optical and X-ray light curves of interacting binaries is still under intensive debate. Vogt (1982) proposed that the superhump modulation is generated at the ‘bright spot’, where the gas stream from the donor star hits the accretion disk. Hessman et al. (1992) investigated a bright outburst (superoutburst) of the dwarf nova OY Car. They suggested that the superhump variation is formed by a large modulation in the surface density of the outer disk that results in a change in the form of the bright spot and / or in the amount of spillover from the accretion stream. Harlaftis et al. (1992) analyzed extensive IUE and Exosat observations of the dwarf nova Z Cha during two superoutbursts and found unexpected dips in its ultraviolet light curve. Billington et al. (1996) used HST data during a superoutburst of OY Car and detected similar dips in its ultraviolet data as well. Harlaftis et al. (1992) and Billington et al. (1996) thus proposed that the superhump variation is due to obscuration of the hottest regions of the accretion disk by the vertical structure at the edge of the disk.

Haswell et al. (2001) pointed out that the dissipation of energy in the accretion disk, which is believed to be the mechanism that gives rise to the optical superhump phenomenon observed in CVs, cannot be applied to LMXBs. They suggested instead that the disk area is changing with the superhump period, and thus predicted that superhumps would mainly appear in low inclination systems. Retter et al. (2002) found superhumps in X-ray data of the dipping LMXB, V1405 Aql (X1916-053), and offered an explanation for the formation of superhumps in high inclination LMXBs. According to their model, the thickening of the disk rim, which causes an increased obscuration of the X-ray source, is the cause of the superhump variation. Retter et al. (2002) further stated that the superhumps in LMXBs could be generated by a combination of both scenarios.

The radio emission in Algol consists of a quiescent component and a flaring part. Imaging observations indicate that the radio emission originates from the polar regions of the cool secondary star. While the quiescent emission occupies an extended region above the polar zone, flares occur in a more compact region near the stellar surface (Mutel et al. 1998; Favata et al. 2000). The emission is circularly polarized, with opposite polarity for the emission from the two polar regions, suggesting a dipolar magnetic field structure, and that the emission is an optically thin gyrosynchrotron radiation from mildly relativistic electrons (for details, see Mutel et al. 1998).

The mass-gainer primary in Algol is a late B star whose envelope is radiative. The radio emission in Algol systems thus has been ascribed to the cool subgiant companion star, which, in contrast, has a thick convective envelope where dynamo processes could operate efficiently to produce magnetic activity (Favata et al. 2000). At a first glance, it is puzzling that the observed 3-d periodicity in the radio light curve of \( \beta \text{ Per} \), if it is a superhump phenomenon as those occur in optical and X-ray bands in CVs, is caused by an accretion disk or an annulus around the mass-receiver star.
that it transfers to the B star is threaded by magnetic field lines, and the magnetic field carried in the accreting material is dragged, twisted and amplified in the closest to the secondary star. However, we do not expect to see activity when the elongated side of the disk / annulus is the metric accretion disk / annulus, which causes enhanced flare can now be explained in terms of the precession of an asymmetric accretion disk / annulus, which causes enhanced flare activity when the elongated side of the disk / annulus is the closest to the secondary star. However, we do not expect to see any superhump activity in the power spectrum of the quiescent component of the emission, consistent with our findings (Section 2, Fig. 3). Our model should reproduce a periodicity at about twice the superhump period as well. It is interesting to note that such a signal is indeed seen in the radio light curve of \( \beta \) Per (Figs. 1–3), but this weak feature may be alternatively explained by a possible deviation of the mean shape of the 3.037-d variation from a pure sinusoid (Fig. 4).

Our scenario for the magnetic activity of \( \beta \) Per is analogous to that in the RS CVn systems, where the radio emission is caused by the stellar magnetospheric interaction. In fact, the radio properties of the Algol and the RS CVn systems are very similar (e.g., Richards & Albright 1993; Umana et al. 1998). In particular, the circular polarization in the radio of \( \beta \) Per and the RS CVn system, V711 Tau (HR 1099), are almost identical (Mutel et al. 1998). We believe that the only difference is that the magnetism in \( \beta \) Per and Algol systems is caused by the interaction of a magnetic star and a disk / annulus created by the field threaded material transferred from the magnetic star, while RS CVn systems like V711 Tau consists of two detached stars both of which exhibit magnetic activity.

Umana et al. (1998) detected radio emission in six out of 26 Algol systems surveyed. The radio emission of \( \beta \) Per, which probably represents the Algol systems, is highly variable with strong flares (Richards et al. 2003) and therefore, the significance of this work is mainly in the statistics. We believe that the major reason why so few Algols are not observed with strong radio activity is that they are too far away. Other systems may be older than expected (e.g., \( \delta \) Lib) and older cool stars have weaker magnetic fields than young stars of similar spectral type. \( \beta \) Per is far more active than the other systems simply because it is the closest of the Algols, and the strength of the radio flux decreases with the square of the distance. We note that the fraction of Algols with radio detection is significantly larger than the fraction of magnetic accreting systems such as magnetic CVs, among which only AE Aqr and AM Her have very firm radio emission detections (Dulk et al. 1983; Bookbinder & Lamb 1987; Bastian et al. 1988; Beasley et al. 1994). A comparison between RS CVn systems, Algols and magnetic CVs leads us to speculate that the flux density could also be related to the size of the regions where reconnection occurs and relativistic electrons are accelerated. Further observations and theoretical studies will test this hypothesis.

To summarize, the radio emission in the model that we propose for the Algol-like binaries has the following characteristics. Firstly, the emission is expected to be strongest in the polar region of the secondary star where the field is the largest and the converging dipole fields focus the trapped relativistic electrons, which have been accelerated by field reconnection in the magnetic disk / annulus around the B star. This is in contrast to emission from star spots in isolated magnetic stars, which have no strong location preference, and to emission from electrons trapped in an equatorial dead zone of single magnetically active stars. Secondly, the emission from the two polar regions should have different handedness (left or right) in the circular polarization, indicating the dominant influence of the secondary’s global dipole field, which focuses the relativistic electrons to the secondary’s poles and interacts with the tangled fields in the primary’s magnetic disk / annulus. Thirdly, the quiescent component of the radio emission should not show the superhump period, as the electrons responsible for the quiescent emission are aged electrons which have been accumulated in many reconnection and flaring events. However, the superhump period could be detected in strong radio flares caused by episodic enhancement of field reconnection when the asymmetric disk precesses, as there is an injection of a fresh population of relativistic electrons.

### 3.2. Further considerations

Initially, the X-ray emission from the Algol systems was connected with the accretion between the binary stars (Schnopper et al. 1976; Harnden et al. 1977). It is now accepted that the origin of the X-ray radiation is the secondary cool star (e.g., White et al. 1980; Favata et al. 2000).

Recently, Chung et al. (2004) confirmed this concept by finding Doppler shifts caused by the orbital motion of the secondary star in several emission lines in Chandra X-ray data of \( \beta \) Per. The measured shifts were, however, slightly smaller than the expected values. Therefore, Chung et al. (2004) suggested that
either the primary star contributes about 10-15% of the X-ray light, thus shifting the center of mass away from the secondary star or that its surrounding corona is distorted towards the primary. The second option is consistent with our model for the magnetic activity in $\beta$ Per presented above since the locations of the two B regions at the magnetic poles of the K-star in Figure 5 are inclined towards the B-type primary star. In line with the ideas presented in our work, we suggest that an alternative (or complimentary) simple solution to the above inconsistency is that the accretion ring around the primary star contributes some of the extra X-ray light that is required in order to decrease the Doppler shifts in the emission lines. This proposed solution is in agreement with the hydrodynamic results of Blondin et al. (1995) who found that the disk temperature in Algol should get as high as $10^6$ K corresponding to X-ray energy.

Assuming that the observed peak at $\sim$3-d is a true superhump, the mass ratio of the binary system of $\beta$ Per can be estimated from the superhump period excess over the orbital period (about 6% – Sections 1–2). From Osaki (1985) we find $q=\frac{M_{\text{d mass}}}{M_{\text{_rec}}}=0.29\pm0.01$. Using the simulations presented by Murray (2000), a mass ratio of $q=0.16\pm0.04$ is concluded. The unweighted mean of these values ($\sim0.23$) is in agreement with the previous estimates of $q=0.217\pm0.005$ (Hill et al. 1971; Tomkin & Lambert 1978) and $0.22\pm0.03$ (Richards et al. 1988). We note, however, that unlike compact binaries, in Algol systems the bright extended B star may have some gravitational influence on the accretion disk and thus can complicate the calculations for superhumps.

4. SUMMARY AND CONCLUSIONS

We found evidence for a new periodicity about 6% longer than the orbital period in extensive existing radio photometry of $\beta$ Per. The period is seen in the flaring data but not in quiescence. This peak is interpreted as a positive superhump period. The detection of superhumps in the radio light curve of $\beta$ Per implies that it had some sort of an asymmetrical accretion structure that maintained its eccentricity for nearly six years. We propose that it is an accretion disk or a ring. This suggestion is consistent with interpretation of optical data, Doppler tomography and numerical simulations that imply that $\beta$ Per has an accretion annulus around its primary B star. Therefore, Algol systems with short orbital periods may have accretion disks / rings / annuli that may be more stable than what was previously believed. In our model, the 50-d period in the radio data is explained as the apsidal precession of the accretion disk / annulus.

Our results extend the superhump phenomenon, which has been observed in Keplerian accretion disks in compact binaries, to accretion structures with sub-Keplerian velocities. It is also the first detection of superhumps in an Algol system and the first time this phenomenon is seen in the radio.

A new model is proposed for the magnetic activity of Algol-like systems. According to our scenario, in addition to the strong magnetic field of the secondary star, the magnetic field carried in the accreting material is dragged, twisted and amplified in the accretion disk / annulus around the primary star. The reconnection of the field lines accelerates electrons to relativistic energies and trapping occurs near the magnetic poles of the cool star. The binary system is thus reminiscent of RS CVn systems, which consist of two magnetically active stars. This model explains several peculiarities in the radio emission of $\beta$ Per. In fact, it may further explain the low flaring activity of $\delta$ Lib (Richards et al. 2003) by the fact that it has a binary mass ratio above the theoretical limit for superhumps (Sections 1–3).

Our model for the formation of the superhump signal in the radio light curves of Algol systems, namely that the reconnection of the field lines varies with the phase of the eccentricity, yields a prediction that Algol binaries with intermediate orbital periods (thus having a transient disk or an accretion annulus) and mass ratios below the critical value for superhumps, 0.33 (Section 1), should be somewhat stronger and harder radio sources than the other objects. Similarly, the radiation in other wavebands may be enhanced compared with systems with larger mass ratios.

Our scenario for $\beta$ Per can further explain the fact that the X-ray Doppler shifts in emission lines of its secondary star are slightly smaller than what would be predicted from its orbital rotation. The accretion disk annulus is proposed to contribute about 10-15% of the total X-ray light. Therefore, we may predict that the X-ray light curve of Algol will be modulated with the superhump period as well.

The binary mass ratios in non-eclipsing Algol systems might be estimated using the superhump phenomenon. Our results should also help to explain some of the observed peculiarities of these systems in the infrared, radio, optical, ultraviolet and X-ray bands and shed new light on the magnetic activity in binary systems and its interaction with the accretion structures.

We hope that future radio and X-ray observations of $\beta$ Per and other Algol-type systems with low mass ratios that should have superhumps would be able to confirm or refute our suggestions.

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