Cyclic Period Changes in Close Binaries: A Light Travel Time Effect or a Symptom of Magnetic Activity?

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Abstract. Years to decade-long cyclic period changes have been observed in many classes of close binaries. A common explanation invoked for these cyclic period changes is the gravitational influence of an unseen third body upon the close binary pair. The effects of an unseen third body must be strictly periodic, and not all of these observed period variations match this prediction. Douglas Hall noted almost 20 years ago that Algol binaries with cyclic period changes always had a convective, rapidly rotating secondary star. This secondary star has the seeds for a powerful magnetic dynamo, and the suggestion was made that magnetic activity was the cause of the observed cyclic period changes.

In this paper I will review the observational evidence for a magnetic cycle driving the observed cyclic period changes. I will also discuss the theoretical framework which now exists to explain how the magnetic cycle can alter the orbital period of a close binary. I will close by discussing an ongoing observational effort to test the predictions of the magnetic activity-cyclic period change connection.

1. Introduction

The light travel time effect (LTTE) manifests itself as a periodic oscillation in a plot of observed minus calculated ($O - C$) times of phenomena in variable stars. Such an oscillation in the $O - C$ plot may reveal the presence of an otherwise unseen companion object(s). A particularly pathological example of the effects of a third body is the cessation of eclipses in SS Lac (Torres & Stefanik 2000; Eggleton & Kiseleva-Eggleton 2001). Cyclic orbital period changes revealed in $O - C$ plots for eclipsing binaries are sometimes interpreted as the manifestation of an unseen companion on the close binary pair. Long-term cyclic period changes are a fairly common phenomenon in close binary systems, Algol (Hall 1989), RS CVn (Hall & Kreiner 1980), and W UMa (Hobart et al. 1994) binaries all exhibit cyclic period changes on decade long timescales. While some of these close binaries with cyclic $O - C$ residual plots do have distant companions the LTTE is not always a good explanation. This was noted as early as 1939 by Dugan & Wright (1939).

In §2 I will attempt to illustrate how the LTTE fails to consistently explain $O - C$ data for Algol, RS CVn and W UMa binaries. In §3 I present some non-LTTE driven mechanisms which fail to explain cyclic period changes. In §4 I will present review the observational and theoretical support for a magnetic
cycle driven model for cyclic period changes. Suggestions for future work appear in §5.

2. Problems for the LTTE Hypothesis

A key prediction of the LTTE of an unseen companion is that the period variation must be strictly sinusoidal [Kopal 1978]. Thus, the year to decades long cyclic orbital period changes in close binaries must be a regular sinusoidal function. Given enough patience on the part of the observer, or a thorough literature search, one can examine the period changes in close binaries for evidence of a strictly sinusoidal residual in the $O - C$ plots. The prototypical Algol $\beta$ Persei provides the longest time baseline I am aware of for examining these cyclic period variations. Algol displays a 32 year period in its $O - C$ data which [Friebes-Conde, Herczeg & Høg 1970] interpreted as apsidal motion. The close binary pair in Algol, Algol AB, has a circular orbit [Söderhjelm 1980] and is thus not likely to show apsidal motion. Additionally, the primary and secondary eclipses of Algol AB do not shift in opposite directions as expected if apsidal motion is the culprit. The lack of a regular sinusoidal pattern in the $O - C$ data for Algol AB [Söderhjelm 1980] makes an LTTE explanation less than satisfactory.

It is possible to infer the parameters of an unseen companion responsible for a supposed LTTE variation in the $O - C$ residuals of an eclipsing binary. [Van Buren 1986] used the eclipse timing residuals for 8 RS CVn systems and determined that only two systems had plausible third bodies. In some systems he found the $O - C$ data implied a neutron star or black hole companion in order to be consistent with the lack of detection of the third body. Although black holes and neutron stars certainly exist the space density of RS CVn systems presents difficulties when one considers the number of massive star progenitors required [Van Buren 1986].

[Borkovits & Hegedüs 1996] carried out a Fourier analysis of 18 close binaries of various classes, and found good agreement to the third body hypothesis for four of the systems. Borkovits and Hegedüs were careful to check that the resulting solutions were physically realistic and compatible with the lack of detection of the third body. Even so, we see a trend emerging that the LTTE hypothesis does not explain all the cyclic period changes observed in close binaries. As different classes of close binaries exhibit the same cyclic period changes a common explanation in the spirit of Occam’s Razor would be most satisfying. The Light Travel Time Effect fails as a common explanation and researchers eventually turned to other explanations.

3. Non-LTTE Explanations for Cyclic Period Changes

Mass transfer between stars in an interacting binary can cause period changes, but does not seem to explain cyclic period variations. In the case of mass transfer which conserves angular momentum and mass [Kwee 1958] showed that mass transfer can only increase or decrease the orbital period, and cannot cause cyclic period variations. [Biermann & Hall 1973] suggested sudden bursts of mass transfer which temporarily stored angular momentum in the rotation of the hot mass-gaining star in Algol systems as a possible cause of cyclic period
variations. The sudden mass transfer event rapidly decreases the orbital period, which then slowly increases as tidal forces return the angular momentum to the binary system. Subsequent work on the Algol U Cep (Olson et al. 1981) failed to demonstrate the gradually changing period required by Biermann & Hall. Non-conservative mass transfer could cause period changes, but not of the cyclic variety seen in the $O-C$ plots (Tout & Hall 1991). By 1991 the mass transfer ideas had begun to be supplanted by a magnetic cycle driven model.

4. Magnetic Cycles and Cyclic Period Changes

In his paper which provided a precise definition of the RS CVn class (Hall 1976) noted that both Algols and RS CVn binaries exhibited cyclic period changes of a similar magnitude, but he suspected at this point that the causes were different. In 1976 the period change mechanism for Algols was connected with mass transfer. RS CVn binaries, which are detached and thus no Roche lobe overflow enables mass transfer, were hypothesized to undergo smaller levels of mass loss perhaps related to winds.

A significant development in our understanding of the cyclic period changes was made by Douglas Hall (1989). In his paper entitled “The Relation between RS CVn and Algol" Hall argued that magnetic activity cycles were the cause of the observed cyclic period variations.

The key piece of evidence in support of magnetic activity as a cause of cyclic period changes is shown in Fig. 1. Fig. 1 shows the mass ratio $Q$ for over 100 Algol binaries versus the spectral type of the secondary star in the binary. Hall shows the types of period changes observed in these Algols by using different symbols which are explained in the caption. The significant finding of Hall was that all (31 out of 31) cases of alternating period increases and decreases occur in systems which have secondary stars later than spectral type F5. These secondary stars have convective outer atmospheres, and combined with rapid stellar rotation from spin-orbit coupling the ingredients for a stellar magnetic dynamo are present (Parker 1979). Hall (1989) proposed a magnetic activity cycle driven by these stellar dynamos to explain cyclic period changes in both RS CVn and Algol binaries, although the details of the mechanism were not specified.

If magnetic activity is responsible for the cyclic period changes in Algols than Algols should exhibit observational characteristics similar to the magnetically active RS CVn binaries. Infrared light curves of the secondary star of Algol show variations similar to that seen in the spotted RS CVn stars (Richards 1990). The Very Long Baseline Array image of Mutel et al. (1998) shows lobes of emission above the poles of the secondary star of Algol which are interpreted as gyrosynchrotron radiation (Fig. 2).

Richards & Albright (1993) presented observational evidence for RS CVn-like magnetic activity in Algols from radio, optical and x-ray indicators. The radio luminosity functions of RS CVn and Algol systems appears similar (Umana, Trigilio & Catalano 1998) but small number statistics may leave this result suspect. A long-term radio monitoring survey showed that both Algol and RS CVn stars have similar levels of radio flare activity (Richards et al. 2003). The radio lightcurves for 2 Algol and 2 RS CVn stars from Richards et al. is reproduced in Fig. 3. Algol it-
Figure 1. Reproduction of Figure 4 from Hall (1989). The character of orbital period changes in Algol binaries is shown in this plot of mass ratio $Q$ to secondary star spectral type. A constant period is indicated with a $-$, increasing period $/$, decreasing period $\backslash$, and alternating period increases and decreases by $X$. A $\bullet$ indicates systems for which no conclusion could be drawn. The vertical line in the middle of the plot separates stars with radiative outer atmospheres from those with convective outer atmospheres.

self had slightly more frequent, though slightly weaker, radio flares as compared to the RS CVn star V711 Tau.
Figure 2. Stokes I VLBA radio image of Algol at 8.4 GHz from Mutel et al. (1998). The shaded oval in the lower left is the FWHM of the synthesized beam of the VLBA. X and Y axes are $\alpha$ and $\delta$ relative to the image center. Contours are 0.8, 1.2, 1.6 and 2.0 mJy beam$^{-1}$.

A theoretical basis for magnetically induced cyclic period variations was introduced by Applegate & Patterson (1987). They proposed a model in which deformations of the active star away from hydrostatic equilibrium changed the gravitational quadrupole moment of the secondary star. As a star went through its magnetic activity cycle the gravitational quadrupole moment was cyclically changed and the period changes reflected the changing quadrupole moment. This model soon required modification when Marsh & Pringle (1990) showed that deviations away from hydrostatic equilibrium were ruled out on energetic grounds.

The energetic problem was solved when Applegate (1992) proposed a model which connected variations of the gravitational quadrupole moment with the distribution of angular momentum in the active star. This required some of the energy from active star’s luminosity to be diverted into differential rota-
Changes in differential rotation then changed the oblateness of the active star and thus the quadrupole moment changed. This diversion of energy from luminosity into differential rotation meant that a cyclic variation in the luminosity of the active star should also occur. The active star transitions between states of hydrostatic equilibrium and therefore radial pulsations are not required. Only differential rotation changes, not the mean radius. A color change is created as the luminosity changes at constant radius, so as luminosity increases the star should become bluer. In summary Applegate (1992) makes three predictions for his magnetic activity model: the light curve and $O - C$ curve should both have cycles of the same length, extrema in brightness should coincide with extrema in the $O - C$ diagram, and the star should be bluest when it is brightest. This model was placed on a firmer theoretical basis by the work of Lanza, Rodonò, and Rosner (1998) and Rüdiger et al (2002). Models for the magnetic dynamos responsible for the cyclic period changes are presented in these two works, and estimates of the sub-surface magnetic field strengths of
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a few kilogauss are made. This theoretical framework than provides a method for probing the internal magnetic structure of stars in close binaries.

Applegate’s three predictions were observed in the RS CVn binary CG Cyg by \cite{Hall1991}. Subsequently \cite{Afサar2004} obtained new photometric measurements of CG Cyg and they claim that two periodicities exist in CG Cyg. A period of 52 years in the \( O-C \) curve is interpreted as evidence for a light travel time effect from a third body of 0.9 M_\odot. \cite{Afサar2004} concur that there is a variation of the average brightness of CG Cyg, but assign to this brightness variation a period of 22.5 years. Thus, CG Cyg may present an interesting case where both the light travel time effect and a magnetic cycle are present. Verification of a magnetic cycle induced period change by means of a varying mean brightness and color is complicated by the long timescale of the variation. Over the decades detector technology changes radically, and different comparison stars complicate the analysis \cite{Afサar2004}.

The Algol binary WW Cyg also apparently satisfies Applegate’s three predictions, but the luminosity and color variations are undersampled in time \cite{Zavala2002,Zavala2004}. In the case of WW Cyg I and my collaborators could not obtain a satisfactory fit to a third body orbit, or a third and fourth body orbit \cite{Zavala2002}. Our preliminary analysis of the color and luminosity variation of WW Cyg at primary eclipse minima did agree with the predictions of the magnetic activity hypothesis. In Table 1 we present a more quantitative analysis of the luminosity and color variations of WW Cyg at primary eclipse minimum. The V magnitudes in Table 1 were produced by averaging data points within 0.0066 days of eclipse midpoint. This is just over 3\( \sigma \) of the worst time of minima estimate in \cite{Zavala2002}. This yields 35 data points in V obtained from 1997 to 1999, and 4 data points for \cite{Hall1972}. \cite{Hall1972} used \( UBV \) filters, and \cite{Zavala2002} used \( VRI \), thus direct comparisons in color index \( B-V \) are not possible. The de-reddened \( B-V \) of 0.82 of \cite{Hall1972} corresponds to a \( V-R \) color of 0.42 \cite{Cox2000}, or a K0V spectral type. We estimated the error in Hall & Wawrukiewicz’s \( V-R \) from the errors presented in their paper. Our estimate of the color of WW Cyg at primary minimum 25 years after \cite{Hall1972} is significantly redder, and corresponds to a main sequence spectral type of K2V. This agrees with the prediction of Applegate that the active star should be reddest when it is faintest, and supports a magnetic cycle driven origin for the period changes in WW Cyg.

| Date  | \( V \)       | \( V-R \)   |
|-------|---------------|-------------|
| 1972  | 13.26 ± 0.01  | 0.42 ± 0.02 |
| 1997–1999 | 13.381 ± 0.003 | 0.48 ± 0.01 |
5. Future Work

Photometric observations of 11 Algol, W UMa, and RS CVn systems are currently underway to test the magnetic activity hypothesis. These systems all show cyclic period variations in their $O-C$ diagrams, and we are obtaining multi-color photometry to examine the correlation between luminosity and color variations as predicted by Applegate. The observations are underway and use the 40 inch (1 meter) reflector at the U.S. Naval Observatory, Flagstaff Station.

A further interesting case is that of $\delta$ Librae, an Algol binary with a third body suggested by [Worek 2001]. This third body is predicted to have a mass of $\approx 1M_\odot$ and a period of 2.76 years. The radio lightcurve of $\delta$ Lib looks relatively quiet compared to Algol (Fig. 3), but $\delta$ Lib may simply have been in a magnetically quiet stage during the observations. $\delta$ Lib is more distant than Algol, but if Algol were at the same distance it would still have a radio flux of 100 mJy, so $\delta$ Lib is certainly radio quiet compared to Algol. The period of 2.76 years proposed by Worek is shorter by a factor of 10 compared to the cyclic period change timescales for Algols. Thus, $\delta$ Lib may present an interesting case of a close binary which should exhibit magnetic cycles, but fails to do so. The predicted amplitude of the barycenter motion is approximately 5 mas, or 1.8 mas yr$^{-1}$. The Navy Prototype Optical Interferometer (NPOI, [Armstrong et al. 1998]) will eventually have 437 m baselines and a resolution of 0.3 mas, and will thus be able to resolve the motion expected by a third body. The superb resolution of optical long baseline interferometry presents a direct method for examining the source of the cyclic period changes in close binaries. The small amplitude of the motion about the barycenter can be measured and the LTTE hypothesis put to a direct test. When combined with the brightness and color variation predictions optical interferometry can provide a convincing test of the validity of magnetically driven cyclic period changes in close binaries.

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