Long-term photometry of the asynchronous polar BY Cam: a period study

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ABSTRACT

Analysis of 15 yr of photometric monitoring of the asynchronous magnetic cataclysmic variable BY Cam leads to revised assignments of the periodicities in the system. The surprising stability of the 197.4-min period suggests that this is the orbital period. We confirm the 7.3-d beat period between the orbital period and the white dwarf spin period, and show that the observed periods of the orbit, spin and beat are consistent to within the errors. In earlier work, the 197.4-min period has been assigned to the $2\omega - \Omega$ sideband. Because of the observed stability of the 197.4-min period in our data, the synchronization time of BY Cam is $>3500$ yr (much larger than that in other asynchronous polars) if the earlier period assignments are adopted. We also suggest that $\sim 145$-d periodicity seen in our data may be due to precession of the rotational pole of the white dwarf.

Key words: stars: fundamental parameters – stars: individual: BY Cam (H0538+608) – cataclysmic variables.

1 INTRODUCTION

Cataclysmic variables (CVs) are semidetached interacting binary systems, in which mass transfer occurs from a Roche-filling lower main-sequence star to its white dwarf companion. If the white dwarf has a strong magnetic field ($B \geq 10$ MG), the mass transfer stream is guided on to the magnetic poles of the accreting star, resulting in a magnetic CV (MCV), or polar. Most polars have been synchronized by magnetic torques, so that the rotation period of the white dwarf is the same as the orbital period of $\leq 5$ h. However, there exists a small category of MCVs in which the spin and orbital periods differ by $\sim 1$–$2$ per cent (Patterson et al. 1995; Campbell & Schwope 1999); magnetic torques acting to reinstate synchronism are expected to result in a slowly changing spin period. Asynchronism in these systems (also known as BY Cam-type MCVs) may be the result of recent nova explosions; however, among the four members of the category, only V1500 Cyg is a confirmed old nova (Stockman, Schmidt & Lamb 1988). In this paper, we present and discuss long-term photometry of BY Cam (=H0538+608), paying particular attention to periodicities that bear on the relationship of the spin and orbital period.

BY Cam was discovered by Remillard et al. (1986) as a bright X-ray source and was identified as a MCV from its strongly polarized light curve. Later, Silber et al. (1992) reported that the white dwarf was suspected to have a spin period shorter than the orbital period by 1.3 per cent. The abnormally strong carbon and nitrogen emission lines in the system (Bonnet-Bidaud & Mouchet 1987; Mouchet et al. 2003) were proposed to be due to the peculiar composition of an evolved secondary, or to an unrecorded nova explosion. In general, the system shows quite irregular behaviour, including X-ray flares (Silber et al. 1992; Ramsay & Cropper 2002), large amplitude modulations with quasi-periodic behaviour (e.g. Silber et al. 1997) and evidence for switching between states of high and low ultraviolet emission (Zucker et al. 1995). The system’s light curve suggests that occasional pole switching occurs due to spin/orbit asynchronism, while $M$ remains the same (Mason et al. 1998). In the Silber et al. (1997) picture of the accretion geometry, a single accreting pole is favoured most of the time, but during intervals of pole switching two poles may be active.

Even among asynchronous polars, BY Cam is poorly understood. The system not only has many anomalous and erratic features in its photometry, spectroscopy and polarimetry, but also shows multiple periodicities whose behaviours change on many times-scales. The latter is probably because the accretion geometry changes within a few orbits, leading to an often-confusing situation in which the detected periods depend on the length of the observations. In general, three periods are detected near 3.3 h. (i) 197.4 min, present in optical photometry, (ii) 199.3 min, seen mostly in X-rays and in polarimetry and (iii) $\sim 201$ min, primarily found in spectroscopic studies. We will refer to these as the 197, 199 and 201 periods, respectively. Mouchet et al. (1997) gave a review and re-analysis of the various periodicities in BY Cam; to these should be added the studies of Silber et al. (1997) and Mason et al. (1998). In this paper, after a short description of our data in Section 2, we present the long-term light curve of the system (Section 3.1) followed by a discussion of the periods emerging from our study (Section 3.2). We finish with our conclusions in Section 4.

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2 DATA

The data were obtained with a 0.41-m robotic telescope (RoboScope) located in central Indiana, which has been operating in unattended mode since 1990, observing ~125 accreting sources; see Honeycutt & Kafka (2004) for details regarding the instrumentation and operations. The BY Cam data were obtained during the interval 1991 August 12 to 2004 November 14, providing a total of 922 usable exposures. An exposure time of 4 min with a $V$ filter was used for all the observations. Nearly all our data consist of one observation on a given night, with a spacing of 1–4 nights. Although we have two exposures per night for 10 per cent of the data, variations within an orbit or a night are not resolved. Data reduction used the method of incomplete ensemble photometry as described in Honeycutt (1992). The error for a given data point is generally 0.01–0.03 mag. Secondary standards from Henden & Honeycutt (1995) were used for the determination of the zero-point for the light curve.

3 DISCUSSION

3.1 The long-term light curve

Our full light curve is shown in Fig. 1 (top). Mason, Liebert & Schmidt (1989) reported BY Cam near $V = 17$ in 1988 December and Szkody, Downes & Mateo (1990) reported $V = 17.5$ in 1989 January/February. This is fainter than any of our 1991–2004 photometry, indicating that BY Cam may have experienced a VY Scl-like low state. VY Scl-type CVs (Hessman 2000; Honeycutt & Kafka 2004) exhibit erratic and abrupt decreases in brightness by several magnitudes. Our photometry suggests that such events are probably rare in BY Cam. As seen in Fig. 1, we found the system mostly near mag 15, with ~1–1.5 mag variations that occur on time-scales faster than our typical sampling interval. By examining photometry in the literature, which adequately samples the orbital period (e.g. Silber et al. 1997), we conclude that the scatter in Fig. 1 is mostly due to orbital variations, accompanied by large changes in the shape of the orbital light curve from cycle to cycle. In ~1995–96 BY Cam was fainter than normal, and some of our data points approach the $V \sim 17–17.5$ level of the reported 1988–89 low state. Recognizing, however, that 1–1.5 mag orbital variations are superimposed, we do not think the 1996–98 behaviour is a true VY Scl-type low state, as the 1989–90 event appears to be. In Fig. 1 (bottom), the light curve is binned into 6-month intervals, revealing a quasi-periodic variation on a time-scale of ~5 yr. Such behaviour in CVs has been suggested to be due to $M$ variations caused by activity cycles on the secondary star (Bianchini 1987; Warner 1988). In Figs 2–4, we show the data of Fig. 1 (top) expanded in panels covering single observing seasons. Figs 2–4 emphasize that most of the scatter in Fig. 1 (top) is unresolved in our data, but there are occasional intervals of systematic trends in mean brightness on time-scales of 30–300 d. There also appear to be intervals during which the unresolved changes have larger amplitude, but this behaviour is difficult to characterize with our data alone.
3.2 Periods

A common modern assignment of the three periods is 201 = orbital motion, 199 = white dwarf spin and 197 = 2ω − Ω sideband (Mason et al. 1995; Silber et al. 1997; Mason et al. 1998), where ω is the spin frequency and Ω is the orbital frequency, as interpreted in the context of the Wynn & King (1992) models of the power spectra of intermediate polars. These period assignments remain somewhat uncertain; in fact both Silber et al. (1997) and Mason et al. (1998) conclude that one cannot rule out that 197 is the spin period. These assignments require that the optical light curve produced by the two poles be identical, in order to ensure that the power at 2ω − Ω greatly dominates the power at Ω (Mason et al. 1998). This might appear to be unlikely, considering that the two major BY Cam accretion regions differ greatly in their hard/soft X-ray ratio and in their X-ray spectral signature (Mason et al. 1998; Ramsay & Cropper 2002). However, AM Her has been known to switch its hard/soft X-ray ratio as a function of orbital phase (the ‘reverse’ mode), with little change in the two optical minima (Heise et al. 1985). Apparently, the optical light curve can rather thoroughly be divorced from the X-ray behaviour in polars, as well as in asynchronous polars such as BY Cam.

Our time-series analysis was performed using a custom implementation of the Scargle periodogram (Lomb 1976; Scargle 1982; Horne & Baliunas 1986). As seen in the periodogram of Fig. 5 (bottom), the 197 peak is quite prominent in our data, and is unexpectedly stable. By examining periodograms of yearly subsets of the data, we find that this period is continuously present and shows no systematic change with time in either frequency or strength. Note that the weaker nearby peaks, reported in optical photometry by Silber et al. (1997) and Mason et al. (1998) at 199.5 and 201.3 min, are not present in our periodogram; their location is marked by vertical dashed lines in Fig. 5 (bottom). The data window function (a periodogram of a constant signal at our data sampling) is very useful for judging the reality of suspected false peaks. However, the ‘grass’ at the floor of our periodogram in Fig. 5 is quite uniform, with no additional peaks of interest apart from the main peak;
therefore, we conclude that the window function has limited utility for this particular case.

The derived ephemeris for minimum light using our 197 period is

\[ HJD = 2444846.98(3) + 0.137120(2)E. \]

Fig. 5 (top) shows the data of Fig. 1 (top) folded on this ephemeris.

The time-scale \( T_s \) for synchronizing the white dwarf rotation to the orbit for the asynchronous systems RX J1940 – 10 and V1500 Cyg was estimated observationally to be 100–150 yr (see Campbell & Schwope 1999, for a summary table). However, based on the observed \( dP_{\text{spin}}/dr \), \( T_s \) in BY Cam is considerably longer (1600 ± 500 yr, Mason & Chandramugam 1992; ~1200 yr, Pirola et al. 1994). The value of \( dP_{\text{spin}}/dr = 0.132 \) s yr\(^{-1} \) derived by Mason et al. (1995, 1998) implies that it will take ~800 yr for BY Cam to reach synchronization. The Mason et al. (1998) spin period derivative is deduced from their reported rate of change in the 197 optical period of 0.26 s yr\(^{-1} \); this is twice \( dP_{\text{spin}}/dr \) if the 197 period is attributed to the 2\( \omega - \Omega \) sideband. The 1σ maximum allowed period change in our 197 peak is 0.014 s yr\(^{-1} \). From that, we calculate \( T_s > 3500 \) yr if our 197 peak is attributed to 2\( \omega - \Omega \) (and \( \Omega \) is constant). This is considerably larger than (i) the observed \( T_s \) of other BY Cam stars, (ii) the earlier estimates of \( T_s \) in BY Cam itself (see above) and (iii) the predicted \( T_s < 1000 \) yr (Andronov 1987) for the class of BY Cam stars as a whole.

As an alternative, let us consider assigning 197 to orbital motion, which is an appealing choice because of 197’s stability in our long-term light curve. It seems reasonable to retain 199 as white dwarf spin because it is detected in hard X-rays and in polarimetry. Furthermore, with 197 assigned to orbital motion, the difficulty of reconciling \( T_s > 3500 \) yr (for \( 197 = 2\omega - \Omega \)) with the much shorter \( T_s \) of other asynchronous polars is removed. If 197 is no longer considered to be 2\( \omega - \Omega \), then \( T_s \) can only be determined by changes in the 199 period. By considering the observed curvature in the (O–C) values of circular polarization measures of the 199 period, Pirola et al. (1994) find \( T_s \sim 1200 \) yr or \( T_s \sim 150 \) yr (depending on cycle count alternatives), with the authors favouring the former value; those values are more consistent with other BY Cam systems.

Our suggested assignment of 197 = orbital leaves open the nature of the ~201-min period despite many published radial velocity studies that have found periods near 201 min. On the other hand, we note that the 201-min periodicity is by far the least accurately determined of the three, with literature values ranging from ~200.4 to 202.8 min (see Mouchet et al. 1997, for a compilation). BY Cam has complex, multicomponent line profiles, which change with phase and epoch, making spectroscopic period determinations difficult. From our observed stability of the 197-min period, we must conclude that either the synchronization time-scale is unexpectedly long, or the earlier period assignments are in error.

Regardless of whether 197 or 201 is designated to be the orbital period, we expect a spin–orbital beat period to occur in the range of 1–3 weeks. Mason et al. (1995) report a photometric beat period of 14.11 ± 0.02 d, while Silber et al. (1997) find a photometric beat period of 7.26 ± 0.01 d, which they believe is half the true beat period of 14.5 d. We searched for meaningful periodogram peaks in our data over the relevant frequency range, finding a relatively strong peak at 7.28 ± 0.01 d, as shown in Fig. 6 (top). In order to assess the reliability of this peak, we produced trial periodograms of synthetic light curves that retained the same IDs (and hence the same window function), but with the magnitudes shuffled among the IDs. Using the periodograms of these shuffled light curves to establish the rms scatter near 7.28 d, we conclude that the peak has

\[ P = 7.28 \pm 0.01 \text{ d, and assuming (as in Silber et al. 1997) that this is half the beat period, we extract } P_{\text{beat}} = 14.54 \pm 0.02 \text{ d. As a consistency exercise, we calculate } P_{\text{spin}} \text{ from our measured values of } P_{\text{orb}} = 0.137120 \text{ d and } P_{\text{beat}} = 14.54 \text{ d, using} \]

\[ P_{\text{spin}}(\text{calc}) = P_{\text{orb}}^{-1} - P_{\text{beat}}^{-1} \text{obs}. \]

We obtain \( P_{\text{spin}}(\text{calc}) = 199.333 \pm 0.002 \text{ min, which is consistent with } P_{\text{spin}}(\text{obs}) = 199.3303 \pm 0.0008 \text{ min (Mason et al. 1998).} \]

Finally, we searched for the precession period of the magnetic poles, suggested by Pirola et al. (1994); the predicted range of 100–150 d was offered as a possible explanation for apparent changes in the inclination of the white dwarf spin axis in BY Cam. A periodogram peak appears at 145 ± 3 d in Fig. 6 (bottom), with a formal confidence limit of ~80 per cent, established using periodograms of shuffled light curves. If confirmed, a precession of the pole of the white dwarf adds another component to the already complicated accretion geometry of the system.

4 CONCLUSIONS

Our suggested period assignments are summarized in Table 1, along with the previous assignments for comparison. Our proposed assignments are supported by (i) the long-term stability of the 197-min period, (ii) the fact that the relationships among the observed \( P_{\text{spin}}, P_{\text{orb}}, \) and \( P_{\text{beat}} \) are consistent to within the errors and (iii) the resulting synchronization times are now more consistent
with expectations. Orbital motion is a strong candidate for the stable 197-min periodicity because orbital angular momentum dominates spin angular momentum in BY Cam. Note that, with our revised period assignments, identical light curves for the two poles are not required to explain 197 as $2\omega - \Omega$. However, it appears that identical light curves are still needed to make $2(\omega - \Omega)$ dominate $\omega - \Omega$ for the 7.3-d period.

The polar configuration in BY Cam is still debated. Silber et al. (1992) conclude that there are two poles located in the same hemisphere of the white dwarf, on the side opposite the secondary star. However, according to Mason et al. (1995), the polar configuration is more complicated than even an off-set dipole geometry, having at least three poles active at times. Mason et al. (1989, 1998) identified two major accretion sites, likely located diametrically opposite one another near the spin equator of the white dwarf. Adding to the complexity of the periodicities is the possible 145-d precession of the magnetic axis and the possibility of oscillations of the primary’s magnetic axis about a locked state, perhaps on time-scales as short as a few decades (Andronov 1987; Campbell & Schwope 1999). It is therefore not surprising that the relationship of the various periodicities in BY Cam have remained puzzling for many years. It is unlikely that our suggested period attributions will be the last word, but we do expect that the stability of the 197-min period in our long-term data will need to be taken into account in future interpretations.

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REFERENCES


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