BG Canis Minoris/3A0729 + 103: the true spin period revealed?

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SUMMARY
We present the results of a Ginga X-ray observation of the intermediate polar BG CMi. The power spectrum reveals for the first time the presence of an 847-s modulation in addition to the accepted orbital and spin periods of ~3.25 hr and ~913 s. 847 s is the beat period between 913 s and 3.25 hr, but implies retrograde rotation of the white dwarf with respect to the orbital motion, something which has never previously been found in cataclysmic variables and which is hard to explain theoretically. The alternative explanation, which we suggest here, is that the spin period of the white dwarf is actually 847 s and that the 913-s modulation represents the beat period. The strong beat modulation provides clear evidence that the accretion in BG CMi does not occur predominantly via a disc and that this modulation arises as a result of the accretion stream flipping from one magnetic pole of the white dwarf to the other every half a beat cycle. The weak X-ray spin modulation may indicate that some accretion occurs via an accretion disc in addition to the predominant stream-fed accretion. This dual accretion mode may be understood in terms of the so-called 'non-accretion disc' model. The X-ray behaviour of BG CMi is similar to TX Col in showing a stronger beat period modulation than spin period modulation, and in fact shows the highest ratio of power in X-ray beat modulation to spin modulation of any intermediate polar. We suggest that the relative strengths of the spin and beat modulations seen in intermediate polars may reflect the relative importance of stream-fed and disc-fed accretion in each system. This in turn may be a reflection of their relative white dwarf magnetic field strengths. We consider how this may be related to the other unique feature of BG CMi, namely the detection of circularly polarized optical/infrared emission.

Key words: accretion, accretion discs – stars: individual: BG CMi – stars: magnetic fields – novae, cataclysmic variables – white dwarfs – X-rays: stars.

1 INTRODUCTION
BG CMi (identified with the Ariel V X-ray source, 3A0729 + 103) is a member of the intermediate polar subclass of cataclysmic variables. It contains a strongly magnetic white dwarf which is accreting, via Roche lobe overflow, from a 15th-magnitude, late-type dwarf star. Optical studies and X-ray observations of the system with Einstein and EXOSAT established its orbital period to be ~3.25 hr and determined a pulse period of ~913 s which was taken to represent the spin period of the white dwarf (M"Hardy et al. 1982, 1984, 1987; Penning 1985). Augusteijn, van Paradijs & Schwarz (1991) have recently presented refined ephemerides for the orbital and pulse periods of BG CMi and show that the white dwarf is in fact spinning up.

As the strong 913-s periodicity has been assumed to represent the white dwarf spin period, BG CMi has been regarded as unusual amongst the intermediate polars in that it is apparently the white dwarf spin period which appears strongly in optical photometric studies. The optical light curves of other intermediate polars, such as AO Psc, V1223 Sgr and TX Col, exhibit much more power at the negative orbital sideband of their spin periods (i.e. the beat period). Modulation of this kind is believed to arise as a result of reprocessing of the X-ray beam off structures fixed in the orbital frame, such as the companion star or an accretion stream impact site distant from the white dwarf. Another
unique feature of BG CMi is that weak circular polarization has been detected, confirming the magnetic nature of the compact object (Penning, Schmidt & Liebert 1986; West, Berrian & Schmidt 1987). No other intermediate polars have been found to exhibit polarized emission (Cropper 1986) and so BG CMi remains the only one for which a direct estimate of the magnetic field strength can be made.

As will be shown below, the data presented here cast some uncertainty on the origin of the 913-s modulation. Therefore, for the time being, we refer to this as simply the ‘pulse period’ with no distinction made as to whether it represents the spin period of the white dwarf in the observer’s frame or in the orbital frame of reference.

2 DETAILS OF THE OBSERVATION

BG CMi was observed by the Ginga Large Area Counter (Turner et al. 1989) for ~24 hr beginning at about 01:30 UT on November 29. Coverage of seven orbital cycles was therefore obtained. Unfortunately, the binary period of BG CMi is almost exactly twice the Ginga orbital period. Hence, because of Earth occultation and passage through the South Atlantic Anomaly, similar portions of the BG CMi orbit were lost on each satellite orbit and the resulting phase coverage is only in two ranges, each about 0.3 of the orbital period wide. The observation was preceded by a long (~17 hr) background observation made on a nearby region of 'blank' sky. This enabled background subtraction to be performed using the method described by Hayashida et al. (1989). The resulting data cube contained 48 energy channels spanning 2–37 keV, with a time resolution of 16 s. The mean X-ray flux of BG CMi during the observation was $1.35 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV), slightly fainter than the earlier EXOSAT detections which were at a level of $1.6 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV).

3 TIME-SERIES ANALYSIS

The time-series data for BG CMi were analysed in four energy bands, namely ~2–4, ~4–6, ~6–10 and ~10–20 keV, with a similar count rate in each band. No significant flux was detected above ~20 keV. In an earlier paper, describing a Ginga observation of the intermediate polar FO Aqr (Norton et al. 1992), we demonstrated the effectiveness of the one-dimensional CLEAN algorithm (Roberts, Lehár & Dreher 1987; Lehto, in preparation) when applied to a Ginga observation of a multiply periodic source. We once again made use of this technique to remove the window function effects from the power spectra of these data. The cleaned power spectrum of the 2–4 keV data shown in Fig. 1 was obtained using a gain of 0.1 and 5000 iterations.

The highest peaks seen are at frequencies corresponding to the orbital period of BG CMi ($\Omega = 1/P_{\text{orb}}$) and the previously determined pulse period ($\omega = 1/P_{913}$). There are also

![Cleaned power spectrum - BG CMi - 2 to 4 keV](image)

**Figure 1.** The 2–4 keV cleaned power spectrum of BG CMi. The inset shows the region around the pulse frequency, indicating significant power at the positive orbital sideband of the pulse.
strong peaks corresponding to one-quarter of the pulse period \((4 \omega)\) and half the orbital period \((2 \Omega)\), and at the positive orbital sideband of the pulse frequency \((\omega + \Omega)\). A further peak at a frequency of \(\sim 1.38 \times 10^{-3} \text{ Hz}\) appears slightly broadened. We note that this frequency is approximately equal to the positive beat between 913 s and the typical length of each observation segment, i.e. \(1.38 \times 10^{-3} \sim \omega + (\Omega/0.3)\). If this is the cause, the width and asymmetry of the peak may be caused by small variations in the total duration of each \(3 \ P_{\text{orb}}\) segment of the light curve. The remaining peaks seen in Fig. 1, at a level of \(\sim 2 \times 10^{-3} \text{ (count s}^{-1})^2\), are not due directly to the window function structure: the last cleansed component in the power spectrum is at a level of \(\sim 10^{-4} \text{ (count s}^{-1})^2\). They may simply be due to noise features in the data or remaining bad data points.

In order to investigate whether any of the structure in the power spectrum is due to the rather special sampling of the light curve imposed by the Ginga satellite orbit, or by the clean technique itself, we performed a number of simulations. In these we constructed light curves with exactly the same time-structure as the original data but containing various combinations of sinusoids and with white noise added. Simulations using two summed sinusoidal modulations (i.e. at \(P_{\text{913}}\) and \(P_{\text{orb}}\) with the same phase coverage as in the actual data) resulted in cleansed power spectra with peaks at only the two input frequencies. When a product term was introduced into the simulated light curve (i.e. amplitude modulation), the cleansed power spectrum showed peaks at both the sideband frequencies \((\omega \pm \Omega)\) with equal power. The only way to obtain a power spectrum that contained only the positive orbital sideband was to introduce such a sinusoidal modulation explicitly into the simulated light curve.

We therefore conclude that the detection of the \(\omega + \Omega\) peak in the power spectrum of the 2–4 keV data is real, as is the absence of the corresponding \(\omega - \Omega\) peak. Neither are artefacts of the time-series structure or the analysis technique used. However, our simulations do not help with an explanation for the 1.38-mHz peak which is clearly present in both the dirty and cleansed power spectra of the 2–4 keV data. None of our simulations produces such a peak, so we have no firm explanation for it.

Power spectra of the time series obtained in higher energy bands are rather more noisy. The pulse frequency and/or its harmonics are apparent in all four data sets, but are by no means the highest peaks at the higher energies where noise features dominate. These relatively high-power peaks are probably due simply to the low signal-to-noise ratio of the data from BG CMI at higher energies. A peak at the orbital frequency is clearly seen in all but the highest energy data set. The \(\omega + \Omega\) sideband peak is not clearly detected above 4 keV.

### 3.1 Orbital modulation

The 2–4 keV power spectrum shows a strong peak corresponding to 11560 ± 210 s which we identify with the orbital period, accurately determined by optical photometry to be 11642.273 ± 0.025 s (Augusteijn et al. 1991). The data folded on the optical orbital ephemeris given by Augusteijn et al. are shown in Fig 2, where phase zero (JD2446694.2888 ± 0.0017) corresponds to optical photometric maximum. It can be seen that the broad X-ray orbital minimum reaches its lowest flux around phase \(\sim 0.45 \pm 0.05\) and there is evidence for a double sinusoidal modulation with a secondary dip occurring at phase \(\sim 0.90 \pm 0.05\).

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**Figure 2.** The data folded at the orbital period of BG CMI (11642.273 s) using the ephemeris of Augusteijn et al. (1991). The four panels represent the four energy ranges shown. Phase zero is optical photometric maximum.

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1984 EXOSAT data reported by M’Hardy et al. (1987) show a similar, double-dip structure with primary minimum at JD2446166.27±0.01. Hence this occurs at phase 0.55±0.07 on Augusteijn et al.’s ephemeris, and the orbital modulations of the two X-ray data sets are therefore in phase with each other.

M’Hardy et al. (1987) referred their X-ray orbital modulation to the ephemeris of Penning (1985), who defined his phase zero (JD2445731.8184) using the point at which the velocity of the hydrogen emission lines crossed the system zero-point from blue to red. (Note that in the text Penning actually says ‘crossing from red to blue’ – this is wrong, see his fig. 3.) Penning assumed that the lines come from an accretion disc and that his phase zero would therefore correspond to the white dwarf lying between the observer and the secondary star (i.e. superior conjunction of the secondary). He further suggested that this point corresponds to optical photometric maximum, so the phase zero of Penning’s and Augusteijn et al.’s ephemerides should agree. However, they do not: Penning’s phase zero occurs at Augusteijn et al’s phase 0.28±0.02. This suggests that either the hydrogen emission region is not localized at the white dwarf or that photometric maximum does not coincide with superior conjunction of the secondary.

Based on these features, we can modify slightly the picture outlined by M’Hardy et al. (1987 – see their fig. 12a). We suggest that the accretion stream from the secondary impacts the white dwarf magnetosphere at a position in the orbit corresponding to phase ∼0.3. This impact and the shocked deceleration of the material gives rise to a region of X-ray emission (Hameury, King & Lasota 1986), which is then obscured by the accretion stream itself over a broad range of orbital phase to give the primary X-ray orbital minimum in the range φ_{orb} ∼ 0.3–0.5 as seen (Fig. 2). The orbital modulation seen in the hydrogen-line radial velocity curves, measured by Penning, is presumably dominated by the motion of this impact region also. Penning suggested that there may be a contribution from more than one source for the line emission, so this does not rule out emission from closer to the white dwarf – which must exist to give rise to the 913-s modulation that he also detected.

3.2 913-s modulation

The X-ray pulse period, determined most accurately from the fourth harmonic of the pulse frequency, is measured to be 913.2±0.3 s in these data. The Doppler correction due to the motion of the satellite with respect to the heliocentre amounts to only ∼+0.06 s on this period and so is negligible within the measurement uncertainty. The X-ray pulse period is therefore consistent with the value obtained from the optical quadratic ephemeris given by Augusteijn et al. (1991), which yields a heliocentric pulse period of 913.4928±0.0002 s at this epoch.

Bearing in mind the orbital modulation discussed above, we divided the data into two orbital phase ranges (φ_{orb} ∼ 0.2–0.5 and ∼0.7–1.0) and folded each at the optical pulse period. The results from this are shown as a function of energy in Fig. 3. It is immediately apparent that the pulse profile cannot be described by a simple sinusoid (as evidenced by the strong harmonic modulation apparent in the power spectra). Rather there are at least two minima per cycle, the relative depths of which vary with energy and orbital phase. Since the modulation is clearly energy dependent, we made similar folds of the softness and hardness ratios to investigate this behaviour. The folds reveal that the source hardens during both the primary minimum (φ_{913} ∼ 0.7) and the secondary minimum (φ_{913} ∼ 0.0). We note, however, that the apparent pulse modulation above 10 keV is marginal, and the folded data are essentially consistent with a constant. The modulation is consistent with the presence of photoelectric absorption. However, because of the relatively large uncertainties in the data, an additional energy-dependent modulation cannot be ruled out. The difference between the folds at orbital maximum and at orbital minimum can also be explained by a varying mean absorption between the two phase ranges.

The X-ray pulse modulation is roughly in phase with the optical pulsaion in that the overall maxima of both occur near phase zero. However, the narrow, secondary X-ray minimum, which is particularly evident at low energies, is superimposed on the pulse maximum. This feature probably indicates that there is a more complex structure in the X-ray emitting region than in the optical.

3.3 847-s modulation

The power spectrum of the 2–4 keV data set clearly shows significant power at a frequency of exactly ω + Ω, whilst there are no significant peaks at the other orbital sidebands of the pulse frequency, ω – Ω, in any of the data sets (see the inset of Fig. 1). Using the optical pulsation and orbital periods (913.4928 and 11642.273 s respectively), we calculate that the positive orbital sideband should be at a period of 847.032±0.002 s. The peak in the power spectrum occurs at 846.7±1.5 s, in agreement with the prediction. The relative phasing of the 913- and 847-s modulations is such that they occur in phase with each other near X-ray orbital maximum. We discuss this below when considering possible causes for the two pulsation periods. Similar behaviour was also seen in the FO Aqr observation (Norton et al. 1992), where a strong negative orbital sideband of the spin frequency was found. As in that case, the asymmetry between the power at the positive and negative orbital sidebands of the pulse period implies that the 847-s modulation cannot be due to an amplitude modulation of the pulse. Rather, as implied by the simulations earlier, it must be an intrinsic property of the system. Furthermore, the lack of significant modulation at 847 s above 4 keV may be understood if this periodic flux variation is caused by a small change in column density in the line of sight. An additional column of a few × 10^{21} atom cm^{-2} at 847-s pulse minimum over and above that at 847-s pulse maximum would only produce a detectable modulation below ∼4 keV, as observed.

We note that no sideband peaks were apparent in the power spectra of either of the EXOSAT observations (M’Hardy et al. 1987) and the current data represent the first detection of such a feature in BG CMi. It therefore joins most of the other well-studied intermediate polars (TX Col, FO Aqr, AO Psc, V1223 Sgr) in showing two spin-related peaks in its X-ray power spectrum.
4 THE ORIGIN OF THE TWO PULSATION PERIODS

We now discuss two possible explanations for the 913- and 847-s modulations which are seen in these data. The first proposal is based on the previous interpretation of 913 s as the spin period, while the second proposal suggests a more radical explanation which, none the less, is actually more physically acceptable.

4.1 Retrograde rotation?

We have noted above that BG CMi is unusual amongst the intermediate polars in exhibiting strong modulation at the same pulse period (i.e. 913 s) in both its optical and X-ray light curves. Many other intermediate polars show their (negative) beat period in optical photometry and the spin period of the white dwarf in X-ray studies. A strong optical spin modulation is not unreasonable, however, and would simply imply that significant optical flux arises at or near the white dwarf surface. However, given the strength of the X-ray pulsation in BG CMi, we would also expect to see a strong reprocessed optical signal, if 913 s is indeed the spin period. No such reprocessed signal has been detected, although admittedly only a limited amount of optical photometry of BG CMi has been published.

The present data, for the first time, reveal the presence of a second modulation period related to the spin of the white
dwarf. Under the previous interpretation, described above, an 847-s X-ray modulation would represent a beat period between the spin and orbit. As noted earlier, however, it cannot be due to amplitude modulation effects, and this poses a problem. Since 847 s is the positive orbital sideband of 913 s, this implies that the white dwarf must be undergoing retrograde rotation with respect to the binary orbit. This will be true irrespective of the way in which the X-ray beat modulation arises, either by reflection at a site fixed in the orbital frame or by the accretion stream flowing from one magnetic pole of the white dwarf to the other (see below). Retrograde rotation of the white dwarf is rather hard to explain theoretically, has never been detected in other cataclysmic variables and, in addition, this scenario still has the problem of explaining the lack of an optical reprocessed signal as seen in other intermediate polars.

4.2 The true spin period?

There is another explanation for the 847- and 913-s periodicities, however, and it is this which we now discuss. If, instead, 847 s represents the spin period of the white dwarf, the 913-s modulation is then the negative orbital sideband of the spin period, i.e. the usual beat period. We note that the argument above relating to the asymmetry between positive and negative orbital sidebands still applies: in this case there is no significant signal at the positive orbital sideband of 847 s (i.e. at ~790 s). Under this interpretation, the X-ray behaviour of BG CMi is similar to that of TX Col (H0542−407; Buckley & Tuohy 1989) in having an X-ray light curve in which the beat modulation is stronger than the spin modulation. A further similarity is that both objects show only the beat period in their optical light curves.

Strong X-ray beat modulation in an intermediate polar cannot be produced as a result of the reflection of spin-modulated X-rays at a site fixed in the orbital frame. First, the albedo of any such site is only ~30 per cent, and secondly, the solid angle which it subtends from the X-ray emission region will be only ~1 per cent. The effect of both of these factors is to reduce significantly the power in any reflected signal to a level far below that observed. This is particularly problematic if, as is the case here and in TX Col, the beat modulation is in fact stronger than the spin-modulated signal. The only way to get around this is to invoke some sort of 'strong beaming' model, as done for example by Buckley & Tuohy (1989) to accommodate the behaviour of TX Col within such a scheme. However, such models are, at best, contrived or physically unrealistic and we prefer a more natural solution to this problem.

A strong beat modulation seen in the X-ray light curve of an intermediate polar therefore provides clear evidence that a significant fraction of the accretion does not occur via a disc (Hellier 1991; Norton et al. 1992; Wynn & King 1992). Passage through a disc washes out all dependence on orbital phase and so means that an intrinsic beat modulation is impossible. The scenario outlined by us to account for the relatively strong beat modulation seen in FO Aqr (Norton et al. 1992) is even more appropriate to BG CMi. As in the case of FO Aqr, we see that the X-ray spin and beat modulations are in phase with each other near X-ray orbital maximum. This occurs naturally in the scenario we outlined in our earlier paper, which we briefly repeat here. The accretion stream from the secondary star impacts the magnetosphere directly where it is decelerated by a shock. The strong X-ray beat modulation then arises as the accreting material attaches to the field lines and is alternately channelled on to one magnetic pole of the white dwarf, then on to the other every half beat cycle. (Remember that the beat period is the rotation period of the white dwarf with respect to objects fixed in the orbital frame, such as the accretion stream.) Furthermore, this will naturally give rise to a beat-pulse profile which varies as a function of orbital phase, as seen in these data. Beat-pulse maximum occurs when the 'upper' magnetic pole preferentially accretes, and beat-pulse minimum when the 'lower' magnetic pole does so. Hence, at X-ray orbital maximum, when the accretion stream is on the far side of the white dwarf, we view the accretion region at the upper magnetic pole from the side at beat-pulse maximum. Conversely, at X-ray orbital minimum, when the accretion stream is between us and the white dwarf, we view the accretion region at the upper magnetic pole from above at beat-pulse maximum (see schematic diagrams in Norton et al. 1992; Wynn & King 1992). Given an asymmetry between the optical depths parallel and perpendicular to the accretion region (King & Shaviv 1984), there is an in-built orbital modulation of the beat-pulse profile.

We have suggested that the relatively weak X-ray spin pulse (at 847 s) probably arises as a result of phase-varying photoelectric absorption as the white dwarf rotates in the observer's frame of reference. The presence of this signal implies that there is some emission which is not modulated at the beat period, i.e. some accretion is occurring on to one or both of the poles at all beat phases. One way in which this could arise is if the switching of the accretion stream from one magnetic pole to the other at the beat period is not quite complete in BG CMi. For comparison, in our earlier paper (Norton et al. 1992) we suggested that in FO Aqr only the balance of the accretion flow switches between the poles, so that the spin modulation is still dominant. Alternatively, Wynn & King (1992) show that a residual spin-pulse modulation would also be present, given even a slight asymmetry between the structure of the two polar accretion regions.

The discussion above shows that stream-fed accretion can explain the X-ray behaviour of BG CMi. However, this does not rule out the possibility that some form of disc exists around the white dwarf. A mode of accretion which has recently been suggested concerns what has become known as a 'non-accretion disc' (King & Lasota 1991, and references therein). In this scenario a truncated disc exists around the white dwarf, giving rise to the usual optical signatures of an accretion disc. However, little or none of the accretion on to the white dwarf actually occurs via the disc. Instead, the accretion stream is supposed to skim over the upper and lower faces of the disc before interacting with the white dwarf magnetosphere. This will then produce all the features of stream-fed, discless accretion as well. Such a model can therefore explain the strong X-ray beat modulation as due to the stream directly feeding the magnetic poles, whilst the weak X-ray spin modulation could arise as a result of a small contribution by disc-fed accretion. The 'non-accretion disc' model has obvious attractions in that it can explain the apparently conflicting signatures of disc-fed and discless accretion which are seen in many intermediate polars. The relative strengths of the X-ray spin and beat modulations...
seen in each system may therefore reflect the fraction of accretion which occurs via each mode of transfer (stream-fed and disc-fed) in each case.

Irrespective of the way in which the weak (847 s) X-ray spin pulse arises, it in turn probably gives rise to a negligible reprocessed optical signal (at 913 s). Since a reprocessed optical signal would emanate from, for instance, the surface of the companion star, it would be out of phase with the X-ray (913 s) beat pulse which arises at the white dwarf. The fact that the 913-s optical pulse is observed to be strong and in phase with the X-ray pulse suggests that the emission responsible for both must come from the same location. We have concluded that the X-ray beat pulse arises at the white dwarf, and not as a result of reflection. Hence, so also must the optical beat pulse, which is therefore not the result of reprocessed radiation. Given the similarities between the properties of BG CMI and TX Col, we suggest that similar behaviour may cause the optical beat modulation in TX Col as well. The detection of circular polarization in BG CMI also implies that some of the optical/infrared flux is produced in a region of high magnetic field, i.e. quite close to the white dwarf. Although the details of the exact process behind the production of polarized emission in BG CMI are still not well understood, this interpretation seems to be consistent with both the optical and X-ray behaviour of BG CMI.

4.3 Why is BG CMI different?

We now consider possible explanations for the unique behaviour which is seen in this system. Since BG CMI is the only intermediate polar from which polarized emission has been unequivocally detected (Cropper 1986; Penning et al. 1986), this suggests that it may possess a stronger magnetic field than the other systems. As a result of this strong field, we may expect that the accretion flow is more closely constrained than in other systems and, because of this, the switching of the accretion stream from one magnetic pole to the other every half a beat cycle may be more complete than in other intermediate polars. If a ‘non-accretion disc’ exists in BG CMI, possibly the high magnetic field reduces the flow of material through the disc still further. The net result of this would be an enhanced beat modulation and a reduced spin modulation, as seen in these data. In other words, the relative strength of the white dwarf magnetic field in intermediate polars may determine how much of the accretion occurs via the disc and how much via the stream, in each case. Another possibility is that the offset angle of the magnetic axis is the dominant factor. If the magnetic axis of the white dwarf is greatly inclined with respect to its spin axis, this too will enhance the fraction of the accretion flow which switches from one magnetic pole of the white dwarf to the other as the magnetic field rotates beneath the accretion stream. Of course, it is also possible that both a high magnetic field and a large offset angle are important, and combine to produce the observed behaviour.

5 SPECTRAL ANALYSIS

The phase-averaged spectrum of BG CMI was found to be equally well fitted using either a simple power law or thermal bremsstrahlung continuum model. A photon index of \(\sim 1.5\) or a bremsstrahlung temperature of \(\sim 50\) keV were appro-

priate. A homogenous absorber was found to provide an adequate fit to the data, unlike FO Aqr where a large low-energy excess was seen and attributed to leakage through a partial covering or patchy absorbing structure (Norton et al. 1992). The main new feature to arise from these spectral data is the confirmation of an iron \(K\alpha\) fluorescence line at \(\sim 6.4\) keV. Although there was some hint of this in the EXOSAT spectra, it was not clearly detected. Allowing both the line energy and equivalent width to vary, the reduced chi-squared fell from \(\sim 4\) in the case of fits without an emission line to \(\sim 2\) when the line was added. The equivalent width of the emission line was determined to be \(\sim 500 \pm 200\) eV at an energy of \(6.37 \pm 0.23\) keV (90 per cent confidence limits). Strong iron \(K\alpha\) lines have now been detected in all well-studied intermediate polars (Norton, Watson & King 1991).

Bearing in mind the interpretation discussed above, we may expect to see evidence in the X-ray spectrum for a second emission site, namely the accretion stream impact region at the magnetosphere. Unfortunately, the data are not of sufficiently high signal-to-noise ratio to warrant the extra model parameters. A two-component bremsstrahlung model does indeed produce an acceptable fit to the data, but the parameters are not well constrained.

These data obtained using the *Ginga* LAC have enabled phase-resolved spectroscopy of BG CMI to be performed for the first time. We divided the data into two orbital phase ranges (as determined by the limited coverage) and into five phase ranges of the 913-s pulse. We therefore had 10 independent orbit/pulse-phase resolved spectra which were fitted with power-law and thermal bremsstrahlung models, each with an emission line (fixed at 6.4 keV to reduce the number of free parameters). Acceptable fits were obtained in all cases. The continuum slope or temperature was found to be essentially constant at all phases. In contrast, the fitted value for the equivalent hydrogen column density was found to vary as a function of both orbital and pulse phase. The minimum value was \(\sim 6 \times 10^{22}\) atom cm\(^{-2}\) at pulse maximum/orbital maximum and the maximum value was \(\sim 20 \times 10^{22}\) atom cm\(^{-2}\) at pulse minimum/orbital minimum. In general the column density was seen to vary in antiphase with the flux, as expected from the hardness ratio folded discussed earlier.

A high column density at X-ray orbital minimum is easily understood in the light of a stream-fed accretion model. Minimum flux represents the phase at which the X-ray source is viewed through the accretion stream impact region. This impact site is presumed to give rise to a ‘splash’ of material as the accretion stream is decelerated by the rotating magnetosphere. A higher column density at the minimum of the beat pulse is also to be expected. Minimum flux on this cycle will be when the accretion stream predominantly feeds the ‘lower’ magnetic pole and its emission is largely obscured by the accretion stream itself.

6 CONCLUSION

The results of the *Ginga* observation presented here have demonstrated that the previously accepted 913-s spin period of the white dwarf in BG CMI must now be taken to represent the beat period of the system instead. The true spin period of 847 s is apparent in the low-energy X-ray light curve, in addition to the previously known periodicities. The
behaviour of BG CMi can be understood in terms of either a discless or a 'non-accretion disc' model. In both of these scenarios, the accretion stream impacts the magnetosphere directly before the accreting material attaches to the magnetic field lines. The result of this is that the accretion flow switches from one magnetic pole of the white dwarf to the other every half a beat cycle and gives rise to the strong 913-s periodicities seen in both optical and X-ray studies.

We have shown that the optical and X-ray 913-s pulsations are in phase with each other and so must both arise from emission close to the white dwarf surface. This is also supported by the previous detections of polarized optical/infrared emission from BG CMi, which indicate that some emission originates in a region of high magnetic field. The weak 847-s spin modulation is probably due to phase-varying photoelectric absorption of X-ray emission which is present throughout the beat cycle. It may arise as the result of a small amount of material accreting via the 'non-accretion disc'. Alternatively, if the flipping of the accretion stream between the magnetic poles every half a beat cycle is not complete, this also produces a residual emission which is unmodulated by the beat cycle and available to be modulated by visibility and/or absorption effects. The uniqueness of this system may be due to either the magnetic field strength of the white dwarf being stronger, and/or the offset angle of the magnetic axis with respect to the spin axis of the white dwarf being larger, than in the other systems. It may be that the relative strength of the white dwarf magnetic field determines how much accretion occurs via a disc and how much via the accretion stream. This will be reflected in the relative power at the spin and beat periods in each intermediate polar: a high beat period to spin period ratio in the power spectrum will indicate a predominantly stream-fed mode of accretion and therefore a higher magnetic field.

Bearing in mind the similarities between the behaviours of BG CMi and TX Col, and the possible explanation for the strong X-ray beat modulation in terms of a high magnetic field, we suggest that TX Col may be a prime candidate for detecting optical/infrared polarized emission. We note that TX Col was not included in Cropper's (1986) fruitless search for polarized emission from several magnetic cataclysmic variables and predict that the white dwarf in TX Col may have a magnetic field strength somewhat lower than that of BG CMi (~5-10 MG: West et al. 1987) but higher than those of TV Col, FO Aqr, EX Hya, AO Psc and V1223 Sgr.

Given that significant optical emission in BG CMi arises in a region of high magnetic field, we would clearly expect to see a periodic variation in the polarized optical/infrared signal. Depending on the orientation of the magnetic field in the emitting region with respect to the line of sight, we may expect to see predominantly linear (viewing perpendicular to the field lines) or circular (down the field lines) polarization. The ratio of linear to circular polarization should therefore vary smoothly on the true spin period. An observation to search for this behaviour may therefore provide a means of confirming the 847-s spin period found using these Ginga data. In contrast, the absolute value of the polarized fraction should vary on the 913-s beat period, as it is determined by the fuelling of each accretion region. We suggest that the region around the dominant X-ray/optical-emitting pole is likely to be optically thick and that the polarization is predominantly seen from the pole which is accreting less. In this case the polarized fraction should vary in antiphase with the optical and X-ray (913 s) pulsations. This too could be checked with a sufficiently high signal-to-noise ratio infrared polarimetric observation.

As a result of considering a large magnetic axis offset angle as a possible explanation for the behaviour seen in BG CMi, we have come to appreciate another interesting feature which it may be possible to observe. All previous explanations of the pulsations seen from intermediate poles have implicitly assumed that the magnetic axis is offset from the white dwarf spin axis. If, instead, an intermediate polar has its magnetic axis aligned with its spin axis, the only modulation to be seen would be at the orbital period of the system. Spin and beat modulations would be entirely absent in both optical and X-ray light curves, whether or not an accretion disc were present. Such 'aligned intermediate poles' may therefore appear very similar to the polars, which are believed to contain synchronously rotating magnetic white dwarfs. They would be distinguishable by their low polarization in comparison with true polars, but it is possible that the current sample of known polars may be hiding one or more of these systems, hitherto unrecognized.

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