Disc precession in the M31 dipping X-ray binary Bo 158?

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ABSTRACT

We present results from three XMM-Newton observations of the M31 low mass X-ray binary (LMXB) XMMU J004314.4+410726.3 (Bo 158), spaced over 3 d in 2004 July. Bo 158 was the first dipping LMXB to be discovered in M31. Periodic intensity dips were previously seen to occur on a 2.78-h period, due to absorption in material that is raised out of the plane of the accretion disc. The report of these observations stated that the dip depth was anticorrelated with source intensity. In light of the 2004 XMM-Newton observations of Bo 158, we suggest that the dip variation is due to precession of the accretion disc. This is to be expected in LMXBs with a mass ratio $\lesssim 0.3$ (period $\lesssim 4$ h), as the disc reaches the 3:1 resonance with the binary companion, causing elongation and precession of the disc. A smoothed particle hydrodynamics simulation of the disc in this system shows retrograde rotation of a disc warp on a period of $\sim 11 P_{\text{orb}}$, and prograde disc precession on a period of $29 \pm 1 P_{\text{orb}}$. This is consistent with the observed variation in the depth of the dips. We find that the dipping behaviour is most likely to be modified by the disc precession, hence we predict that the dipping behaviour repeats on an $81 \pm 3$ h cycle.

Key words: accretion, accretion discs – methods: numerical – galaxies: individual: M31 – X-rays: binaries – X-rays: general.

1 INTRODUCTION

Bo 158 is source number 158 in the catalogue of globular clusters that were identified in M31 by Battistini et al. (1987). Its X-ray counterpart was discovered by the Einstein Observatory (Trinchieri & Fabbiani 1991, source number 81) and is located at $\alpha = 00^h43^m14^s2, \delta = 41^\circ07'26.3''$ (Di Stefano et al. 2002). Trudolyubov et al. (2002) identified the X-ray source as a likely low-mass X-ray binary (LMXB) with a neutron star primary; following their work, we will use the designation ‘Bo 158’ to describe the X-ray source here.

Trudolyubov et al. (2002) report $\sim 83$ per cent modulation in the 0.3–10 keV flux of Bo 158 on a 2.78-h period during the $\sim 60$-ks 2002 January XMM-Newton observation. The modulation resembles the intensity dips seen in high-inclination LMXBs due to photoelectric absorption of X-rays by material that is raised above the body of the accretion disc (White & Swank 1982). The authors comment that the dipping is energy-independent, and discuss two possible mechanisms: obscuration of the central X-ray source by highly ionized material that scatters X-rays out of the line of sight, and the partial covering of an extended source by an opaque absorber. They also report $\sim 30$ per cent dips in the 2000 June XMM-Newton light curve and $\sim 50$ per cent dips in the 0.2–2.0 keV light curve of the 1991 June 26 ROSAT/PSPC observation. However, no significant dips were found in the 0.3–10 keV light curve of the 2001 June XMM-Newton observation; the authors placed a 2$\sigma$ upper limit of 10 per cent on the modulation.

Trudolyubov et al. (2002) obtained fluxes in the 0.3–10 keV band for the three XMM-Newton observations by fitting absorbed Comptonization models to the combined spectra from the EPIC-pn, MOS1 and MOS2 instruments, and concluded that the depth of the intensity modulation was anticorrelated with the source luminosity. We present further XMM-Newton observations and modelling results which suggest that the variation in dipping behaviour may instead be due to precession in the accretion disc. Such behaviour is associated with the ‘superhump’ phenomenon that is observed in interacting binaries where the mass ratio of the secondary to the primary is smaller than $\sim 0.3$ (Whitehurst & King 1991). Superhumps are briefly reviewed in Section 2, followed by details of the observations and data analysis in Section 3 and our results in Section 4. Numerical modelling of the system is discussed in Section 5; the system was simulated by a three-dimensional (3D) smoothed particle
hydrodynamics (SPH) code. We present our discussion in Section 6, and finally our conclusion in Section 7.

2 SUPERHUMPS

Superhumps were first identified in the superoutbursts of the SU UMa subclass of cataclysmic variables (CVs). They are manifested as a periodic increase in the optical brightness on a period that is a few per cent longer than the orbital period (Vogt 1974; Warner 1975). SU UMa are a subclass of dwarf novae with short orbital periods (< 2 h) that exhibit particularly long, bright superoutbursts, separated by several outbursts that are typical of all dwarf novae; the superoutburst intervals are > 5 times longer than the normal outbursts (Vogt 1980).

In the model proposed by Osaki (1989), a superoutburst occurs when a normal outburst is enhanced by a tidal instability; this occurs when the outer disc reaches a 3:1 resonance with the secondary. The disc is small at the start of the superoutburst cycle, well within the radius of tidal instability, and little angular momentum is removed by tidal interaction during the first normal outburst. Hence, the disc cannot accrete all of its mass on to the neutron star, and the size of the disc increases with successive outbursts, until the 3:1 resonance is reached (Osaki 1989). The additional tidal forces exerted on the disc by the secondary at this stage cause the disc to elongate and precess, and also greatly enhance the loss of angular momentum, so that the disc contracts, and most of the disc material is snow-ploughed on to the neutron star, causing the superoutburst (Osaki 1989). The disc precession is prograde in the rest frame, and the secondary repeats its motion with respect to the disc on the beat period between the orbital and precession periods, slightly longer than the orbital period. The secondary modulates the disc’s viscous dissipation on this period, giving rise to maxima in the optical light curve, known as superhumps.

The requirement for the 3:1 resonance to fall within the disc’s tidal radius is that the mass ratio of the secondary to the primary be less than ~0.33 (Whitehurst & King 1991). If we assume that the secondary is a main-sequence star that fills its Roche lobe, then the relation $m_2 \gtrsim 0.11 P_\text{orb}$ holds, where $m_2$ is the mass of the secondary in solar units and $P_\text{orb}$ is the orbital period in hours (e.g. Frank, King & Raine 2002). Hence any accreting binary that has a short enough orbital period may exhibit superhumps. Indeed, there exists a class of short-period, persistently bright CVs that exhibit permanent superhumps (Patterson 1999; Rettter & Naylor 2000).

Haswell et al. (2001) discuss analogous superhump behaviour in LMXBs. Although superhumps have been found in the optical light curves of several black hole and neutron star LMXBs, they cannot be produced by the same mechanism, since the optical output of X-ray bright LMXBs is dominated by reprocessed X-rays. Instead, Haswell et al. (2001) proposed that the modulation is due to variation of the solid angle that the disc subtends to the X-ray source (on the superhump period); in this model, superhumping might be expected to be more prominent in low-inclination systems.

4U 1916 – 053 is a neutron star LMXB, with an X-ray period of 50.00 min and an optical period of 50.4589 min (Callanan, Grindlay & Cool 1995). Haswell et al. (2001) show that LMXBs with orbital periods shorter than ~4.2 h are likely to exhibit superhumps, and identified 4U 1916 – 053 as a persistent irradiated superhumping source. 4U 1916 – 053 is a high-inclination system, with periodic intensity dips in the X-ray light curve (White & Swank 1982). These dips are due to photoelectric absorption by material on the outer edge of the accretion disc; many believe that the inflated bulge on the outer disc rim that is caused by the collision between the gas stream and the outer disc is responsible (see e.g. White & Holt 1982). The X-ray modulation of 4U 1916 – 053 shows striking variability (Smale et al. 1988). These variations repeat on a ~4-d period, and are caused by the precession of the accretion disc (see e.g. Chou, Grindlay & Blomer 2001). When Retter et al. (2002) made power density spectra (PDS) of the X-ray light curve of 4U 1916 – 05, they found peaks corresponding to both the X-ray and optical periods. After removing the dipping intervals, the optical peak was removed; hence the dips were shown to occur on the superhump period. Retter et al. (2002) concluded that that the observed superhumps arose from the same thickened region of the outer disc that caused the absorption of the X-rays, allowing superhumps to be seen in high-inclination LMXBs.

3 OBSERVATIONS AND DATA ANALYSIS

In addition to the three XMM–Newton observations analysed by Trudolyubov et al. (2002), we conducted a programme of four ~20-ks observations over 2004 July 16–19. We present results from our analysis of the archival data, along with three of the four 2004 observations; the other observation suffered from flaring in the particle background over 90 per cent of the observation and is not considered further here. A journal of observations is presented in Table 1.

We analysed data from the pn, MOS1 and MOS2 instruments, which share the same 30 × 30 arcsec$^2$ field of view. We used version 6.0.0 of the SAS software suite$^1$ to obtain the data products, as well as the latest calibration data. For each observation, we selected a circular extraction region with a 40-arcsec radius, centred on Bo 158, and an equivalent source-free region for the background. The background region was on the same chip as the source, and at a similar angular offset from the optical axis. We extracted light curves from the source and background regions in the 0.3–10, 0.3–2.5 and 2.5–10 keV energy bands with 2.6-s binning; these were analysed using FTOOLS version 5.3.1. We also obtained pn spectra of the source and background regions in 4096 channels of 5 eV, and generated response matrix and ancillary response files from the source spectral files. The spectra were then grouped for a minimum of 50 counts per bin. Spectral analysis was performed using XSPEC 11.3.1.

4 RESULTS

The 0.3–10 keV EPIC (MOS1 + MOS2 + pn) light curves of Observations A1–A3 are presented in Fig. 1, with x- and y-axes set to the same scale, and with 200-s binning. Most striking is Observation A3, with six dipping intervals on a 10017 ± 50 s period (Trudolyubov

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Table 1. Journal of XMM–Newton observations of the M31 core. A1–A3 are available in the public archive, while P4–P6 are proprietary observations. Two observations were made during 2004 July 19; the first observation (a) started at 01:42:12, and the second (b) started at 13:11:22.

| Observation | Date       | Exp | Filter |
|-------------|------------|-----|--------|
| A1          | 2000 June 25 | 34 ks | Medium |
| A2          | 2001 June 29 | 56 ks | Medium |
| A3          | 2002 January 6 | 61 ks | Thin   |
| P4          | 2004 July 17 | 18 ks | Medium |
| P5          | 2004 July 19a | 22 ks | Medium |
| P6          | 2004 July 19b | 27 ks | Medium |

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$^1$ http://xmm.vilspa.esa.es

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the depth of that of Fig. 1. The most prominent feature is the dip in P5; it has a period of Trudolyubov et al. (2002).

Times when dipping is expected are labelled ‘D’, using the deepest part of the dip in P5 as time zero, and the period of Trudolyubov et al. (2002), we identified the expected times of dipping, labelled ‘D’, in P4 and P6, using the deepest part of the dip in P5 as phase zero.

In the P4 light curve, there is no evidence for dipping during the first expected dip interval, but some evidence of dipping ∼4000 s after the second interval, 20 cycles away from the dip in P5. Hence, this possible dip would require a period that is either ∼200 s shorter or ∼320 s longer than the 10017 s given by Trudolyubov et al. (2002). However, there is no other evidence for these other periods in the light curves of P4, P5 or P6; hence it is clear that the dipping behaviour of Bo 158 evolves on a time-scale of a few days, just like that of 4U 1916–053.

Several emission models were fitted to the 0.3–10 keV pn spectral energy distribution (SED) of P4, each suffering absorption by material in the line of sight. P4 was chosen because it had the longest interval of persistent emission that was not contaminated by background flares; the resulting source spectrum contained ∼2200 counts. We applied the two models that Trudolyubov et al. (2002) used to model the spectra of A1–A3, namely a power-law (PO) model and a Comptonization model (COMPTT in XSPEC). We also applied a two-component model. The emission of many Galactic LMXBs has been successfully described by a model consisting of a blackbody (BB) and a cut-off power law (e.g. Church & Bahučińska-Church 1995; Church et al. 1998; Barnard, Church & Balucińska-Church 2003); we approximate this model to a BB + PO model, because of the narrow pass band. Table 2 shows the best fits to the spectrum with each model; uncertainties are quoted at the 90 per cent confidence level.

We find that the best-fitting parameters for the PO and COMPTT models agree well with the values presented by Trudolyubov et al. (2002); however, the two-component model provided the best fit. We present the unfolded SED for the two-component fit in Fig. 3; the emissions from the BB and PO components are shown separately. We see that the BB dominates the emission above 1.5 keV. We find a 0.3–10 keV flux of ∼2 × 10^{-12} erg cm^{-2} s^{-1} for all the fits to the P4 data; this gives a 0.3–10 keV luminosity of ∼1.4 × 10^{38} erg s^{-1}, assuming a distance of 760 kpc (van den Bergh 2000).

We then extracted the SED from the interval of persistent emission in P5 indicated in Fig. 3 by a horizontal line. The resulting background-subtracted SED contained 452 counts in the 0.3–10 keV band, which we divided into 10 spectral bins. The spectral shape of the P5 SED was consistent with that of P4, with a luminosity of 1.2 ± 0.2 × 10^{38} erg s^{-1}. Hence the luminosity of persistent emission in P5 is consistent with that of P4 within 3σ.

The depth of dipping in A1 varies from ∼0 to ∼70 per cent with no significant change in the mean intensity, suggesting that the amplitude of dipping is not simply anticorrelated with the source luminosity. Instead, the variation in dipping behaviour may be caused by disc precession. This hypothesis motivated our simulation of the accretion disc in Bo 158, using 3D SPH, discussed in Section 5.

The light curves of XMM–Newton observations of Bo 158 show no eclipses; hence, we know that we are not viewing the system edge on. If the disc were tilted with respect to the binary plane, and precessing, then one might expect to observe dips in some part of the disc precession cycle, but not in others. Dipping is observed throughout Observation A3; this suggests that the dipping phase in the disc precession cycle lasts ≥60 ks. The A1 light curve covered three intervals of expected dipping, yet only one dip is seen, toward the end of the observation; we suggest that this dip signals the onset of the dipping phase. Contrariwise, P5 and P6 appear to sample the end of the dipping phase, as a dip is observed in P5, yet no dips are seen in P6.

**Figure 1.** Combined EPIC 0.3–10 keV light curves (in count s^{-1}) of Bo 158 from the archival XMM–Newton observations, A1–A3; the dates of each observation are shown.

**Figure 2.** Combined EPIC 0.3–10 keV light curves (in count s^{-1}) of Bo 158 from the 2004 XMM–Newton observations, P4–P6; the dates of each observation are shown. The horizontal line in the P5 light curve indicates the interval used for spectral fitting. The shaded area of the P6 light curve shows the interval of expected dipping at ∼8 and ∼18 ks into the observation. In this regard, Observation A1 resembles the 1985 October light curve of 4U 1916–053, observed by EXOSAT, where deep dips were observed only after the first four orbital cycles (Smale et al. 1988). Little evidence of variability is seen in the light curve of Observation A2.

In Fig. 2, we present the 0.3–10 keV EPIC light curves of Observations P4–P6; the x-axis is scaled to P6, and the y-axis matches that of Fig. 1. The most prominent feature is the dip in P5; it has a depth of ∼100 per cent and a total duration of ∼2500 s.
5 SPH SIMULATION OF THE DISC

5.1 Binary parameters

The accretion disc was modelled using a 3D SPH computer code that has been described in detail in Murray (1996, 1998), Truss et al. (2000) and Foulkes, Haswell & Murray (2005). We assumed the orbital period to be 10017 s, as obtained by Trudolyubov et al. (2000). The SPH parameters were set to \( \alpha = 0.1 \) and \( \alpha = 0.025 \), where \( \alpha \) is the binary separation, and the viscosity state changed smoothly as described in Truss et al. (2000). The SPH smoothing length, \( h \), was allowed to vary in both space and time and had a maximum value of 0.01\( \alpha \).

### 5.1.1 The gas stream

We simulated the mass loss from the secondary by introducing particles at the inner Lagrangian point \( (L_1) \). The mass transfer rate and the particle transfer rate were provided as input parameters, and the mass of each particle was derived from these parameters. A particle was inserted with an initial velocity (in the orbital plane) equal to the local sound speed of the donor, \( v_s \), in a direction prograde of the binary axis. The \( z \) velocity of the inserted particle was chosen from a Gaussian distribution, with a zero mean and a variance of 0.2.

| Parameter | \( M_1 \) (\( M_\odot \)) | \( P_{\text{orb}} \) (d) | \( M_{\text{acc}} \) (\( M_\odot \) yr\(^{-1} \)) | \( q \) | Physical luminosity \( (L_\ast) \) (erg s\(^{-1} \)) | \( L_\ast/L_{\text{Edd}} \) |
|-----------|----------------|----------------|----------------|---------|---------------------------------|----------------|
| Value     | 1.8            | 0.1159         | 2.22 \times 10^{-8} | 0.2     | 1.4 \times 10^{38}             | 0.8             |

For the secondary, we considered a main-sequence star and a white dwarf, since 4U 1916 – 053 has a likely white dwarf secondary (e.g. Chou et al. 2001). For a Roche lobe filling main-sequence star the approximate relation \( m \approx 0.11P_\text{orb} \) holds (e.g. Frank et al. 2002), giving a mass of \( \sim 0.30 M_\odot \). If instead the star is a white dwarf, using the mass–radius relation of Nauenberg (1972) and Roche geometry gives an implausibly small mass of 0.005 \( M_\odot \). Assuming a main-sequence secondary, we found the mass ratio to be 0.2, indicating that superhumps and disc precession were likely.

Finally, the luminosity of the system was taken to be \( 1.4 \times 10^{38} \) erg s\(^{-1} \), the 0.3–10 keV luminosity of Bo 158 in Observation P4. Such a high luminosity may be expected to cause warping of the accretion disc, even for a previously flat disc (see e.g. Pringle 1996); warping is discussed in Section 5.3.

The accretion disc had an open inner boundary condition in the form of a hole of radius \( r_1 = 0.025a \), where \( a \) is the binary separation, centred on the position of the primary object. Particles entering the hole were removed from the simulation. Particles that re-entered the secondary Roche lobe were also removed from the simulation as were particles that were ejected from the disc at a distance > 0.9\( a \) from the centre of mass.

We assumed an isothermal equation of state and that the dissipated energy was radiated from the point at which it was generated, as electromagnetic radiation. Shakura & Sunyaev (1973) viscosity parameters were set to \( \alpha_{\text{low}} = 0.1 \) and \( \alpha_{\text{high}} = 1.0 \), and the viscosity state changed smoothly as described in Truss et al. (2000). The SPH smoothing length, \( h \), was allowed to vary in both space and time and had a maximum value of 0.01\( \alpha \).
was injected into the simulation every 0.01 and with the central radiation source switched off. A single particle inserted at the described above until a quasi-steady mass equilibrium was reached.

5.1.2 The initial non-warped accretion disc

The simulation was started with zero mass in the accretion disc and with the central radiation source switched off. A single particle was injected into the simulation every 0.01Ω−1 at the L1 point as described above until a quasi-steady mass equilibrium was reached within the disc. This was taken to be when the number of particles inserted at the L1 point, the mass transfer rate, was approximately equal to number of particles leaving the simulation at the accretor, the accretion rate. The simulations were continued for another three orbital periods to ensure mass equilibrium. The number of particles in the simulated accretion disc was approximately 40 000 giving a good spatial resolution; the average number of ‘neighbours’, i.e., the average number of particles used in the SPH update equations, was 8.2 particles. The simulated disc encountered the Lindblad 3:1 resonance and became eccentric. The disc precessed in a prograde direction giving rise to superhumps in the simulated dissipation light curves (cf. Foulkes et al. 2004). The radiation source was then turned on which gave rise to a very small number of particles being ejected from the accretion disc.

5.2 Surface-finding algorithm and self-shadowing

Accretion-powered radiation from the inner regions of the disc and the accreting object exert a force on the irradiated disc surface. Following Pringle (1996) the radiation source is modelled as a point source at the centre of mass of the accretor. To apply this force, particles on the surface of the accretion disc had to be identified. We used a convex hull algorithm to find the surface particles as described in Murray (1998) and Foulkes et al. (2005). A ray-tracing algorithm was used to determine regions of self-shadow. For each particle found on the disc surface a light ray was projected from the particle to the position of the radiation source at the centre of the disc. The particle was deemed to be illuminated by the radiation source if this light ray did not intersect any disc material between the particle surface position and the radiation source (i.e., the particle could be visible from the radiation source). The radiation force was only applied to particles that were considered to form part of the disc surface and were illuminated by the central radiation source.

5.3 Disc warping and precession measure

For an optically thick disc, a warp can develop as a result of the radiation force (e.g. Pringle 1996; Ogilvie & Dubus 2001; Foulkes et al. 2005). This is due to the fact that any radiation absorbed by a specific region on the disc surface will be later reradiated from the same spot, normal to the disc surface. Hence any anisotropy in the disc structure will cause an uneven distribution of back-reaction forces on the disc surface, further perturbing the disc. A sufficiently high luminosity can induce and sustain a warp even in an originally flat disc (Pringle 1996, and references therein).

The two measures defined by Larwood & Papaloizou (1997) were used to measure the disc warping and the amount of warp precession. They defined an angle $\theta$ as the angle between the total disc angular momentum vector and the angular momentum vector for a specific disc annulus, i.e.,

$$\cos \theta = \frac{J_A \cdot J_D}{|J_A||J_D|}$$  \hspace{1cm} (1)

The term $J_A$ is the total angular momentum within the specific annulus and was calculated by summing the angular momentum for each particle within the annulus. The term $J_D$ is the total disc angular momentum and was calculated by summing all the angular momenta for all particles within the disc. An angle $\Pi$ was also defined which measures the amount of precession of the disc angular momentum relative to the initial binary orbital angular momentum, $J_O$, i.e.,

$$\cos \Pi = \frac{(J_O \times J_D) \cdot u}{|J_O \times J_D||u|}$$  \hspace{1cm} (2)

where $u$ is any arbitrary vector in the binary orbital plane.

5.4 Numerical modelling results

Prior to irradiation, the disc was asymmetric about the binary axis and precessed in a prograde direction relative to the inertial frame. After switching the radiation source on we ran the model for a further 50 orbital periods, and found that this illumination introduced a warp in the disc. When the radiation source was removed, the warp would dissipate and the disc would return to the orbital plane.

As a result of the disc precession, viscous stresses in the disc vary significantly with time. Fig. 4 shows how the resultant energy dissipation in different regions of the disc varies with time. The disc luminosity was not modelled in detail. We assume that the luminosity was directly related to the disc regions with significant energy release through viscous dissipation. The viscous dissipation heats the gas in the accretion disc and it is assumed that the heat is radiated away from the point at which it was generated. Superposed on a steady signal there is a repeating series of ‘humps’. The spacing of the humps corresponds to the superhump period. The humps consist of three separate major components. The maximum occurs at phase ~0.2, followed by a secondary maximum at phase ~0.5 and the minimum at ~0.7; however, the relative strengths of the humps...
vary from cycle to cycle. We stress that the dissipation light curves are only a diagnostic for the disc properties, i.e., for identifying the superhumps, as well as the intervals when the disc structure is most extended or most compressed. They are not representative of true optical light curves.

In order to determine the superhump period, $P_{\text{sh}}$, we obtained a power density spectrum from $\sim 30$ superhump cycles of the simulated light curve. We estimated the superhump period to be $(1.035 \pm 0.005) P_{\text{orb}}$. This implies the precession period of the outer regions, $P_{\text{prec}} = (29 \pm 1) P_{\text{orb}}$, or $81 \pm 3\text{h}$.

Fig. 5 contains projection plots for the time period corresponding to the peak labelled ‘max1’ in Fig. 4, at phase $\sim 2.2$. A very strong spiral density compression wave can be seen at the upper edge of the disc. This wave is so intense that it is removing material from the accretion disc and returning it back to the Roche lobe of the secondary; see Foulkes et al. (2004) for a full detailed description of a similar system with a mass ratio of 0.1.

The two upper right-hand plots of Fig. 5, labelled $yz$-view and $xz$-view, are side views of the disc in the $y$-$z$ and $x$-$z$ directions, respectively. The $yz$-view plot is a projection view of the disc as seen from the secondary, similarly the $xz$-view is a projection plot with the secondary located to the right of the plot. The disc warp is clearly apparent in these two plots. The warp is odd symmetrical about the centre of the disc. The maximum value of the warp is located at a distance approximately $0.1\eta$ either side of the primary position; see $yz$-view of Fig. 5.

The lower plot of Fig. 5, labelled accretor-view, shows the distribution of the particles as seen from the compact object. The horizontal axis is the binary orbital phase, $L_1$ is located at phase 0 and disc material flows from right to left out of the orbital plane. The warp reaches a maximum height above the orbital plane at phases $\sim 0.1$ and $\sim 0.6$, and has minima at phases $\sim -0.45$ and $\sim -0.95$. We also see that the disc remains mainly in the orbital plane, although it can be seen that there is a small $S$-wave in the structure of the disc.

The warp amplitude and size precessed as a solid body in a retrograde direction relative to the inertial frame. The warp precession period, $P_{\text{warp}}$, was determined by applying equation (2) to each time-step of the simulation. This gave a precession angle relative to some arbitrary start angle for each simulation time-step. The warp precession rate was then determined by fitting a straight line to these data using a numerical recipes least squares method (Press, Flannery & Teukolsky 1986). The precession rate was found using the gradient of the line extracted from the least squares fit. We found that $P_{\text{warp}} \sim 11P_{\text{orb}}$. Fig. 6 shows the radial profile of the warp for

Figure 5. Particle projection plots for the SPH model. The position of each particle is indicated by a small black dot. The plot labelled $xy$-view is a plan view of the accretion disc as seen from above the disc. The cross at the centre of the plot shows the position of the primary object. The solid dark line is the Roche lobe of the primary and the $L_1$ point is to the right and middle of the plot. The two plots $xz$-view and $yz$-view are particle projection plots on a plane perpendicular to the orbital plane and through the system axis. The bottom plot, accretor-view, shows the particle distribution as seen from the compact object. The horizontal axis is the orbital phase, the $L_1$ point is at phase 0 and the stream/disc impact region is at approximately phase 0.9. The vertical axis is the angle, in degrees, between a particle and the orbital plane when viewed from the compact object. The disc material flows from right to left.

\[ \begin{align*}
\text{Normalized binary separation} \\
\text{xy-view} & \quad \text{yz-view} \\
\text{xz-view} & \quad \text{accretor-view}
\end{align*} \]
We report a single ~100 per cent dip in the 0.3–10 keV EPIC light curve of Bo 158 from Observation P5, but find little evidence of dipping in Observations P4 and P6. Trudolyubov et al. (2002) propose two models to explain the energy independence of dipping that they inferred from Bo 158: (1) absorption by a highly ionized region and (2) partial covering of an extended source by an opaque absorber that occults varying fractions of the source. However, in their figure showing both non-dip and dip SEDs, the two SEDs converge at high energies, showing that the dipping is indeed energy dependent.

The dipping behaviour of many Galactic LMXBs has been well described by a single model: absorption of a point-like BB plus progressive covering of an extended emission region by an extended absorber (Church et al. 1997). This extended emission is caused by unsaturated inverse-Comptonization of cool photons on hot electrons in an accretion disc corona that has a radius of ~10000–500000 km (Church & Balucinska-Church 2004). The saturated dipping observed by 4U 1624 – 490 during a 1985 EXOSAT observation is particularly strong evidence for an extended absorber (Church & Balucinska-Church 1995). The 0.1–200 keV observations of 4U 1916 – 053 with BeppoSAX have shown that the absorber is so dense that ~100 per cent photoelectric absorption occurs up to 10 keV; in fact, the dipping is seen up to 40 keV (Church et al. 1998). However, the high luminosity of Bo 158, together with the large blackbody contribution, means that the dipping is unlikely to be energy independent.

Disc precession is inferred from the 0.3–10 keV light curves of Bo 158, as is expected given its extreme mass ratio (short orbital period). As such, it resembles the Galactic superhumping LMXB 4U 1916 – 053. Since the LMXB Bo 158 is in a globular cluster near the centre of M31, it is unlikely that the optical period will ever be known. However, our Fourier analysis of the simulated dissipation light curves indicates a superhump period that is 3.5 ± 0.5 per cent longer than the orbital period. Given the association between the dips and superhump period reported by Retter et al. (2002), the 10017-s period may be the superhump period, in which case the orbital period would be ~4 per cent shorter. Such shortening of the period would not dramatically affect the outcome of our SPH modelling.

Our simulations of the disc show two distinct types of variability in the disc structure. First is the elongation and prograde precession of the disc due to tidal interactions with the secondary at the 3:1 resonance; the disc precesses on a period of 81 ± 3h. We also see warping of the accretion disc, driven by irradiation of the disc surface by the central X-ray source; the warp is stable and exhibits retrograde precession on a ~31-h period.

It is therefore important to establish which region is responsible for the observed variation in dip morphology. The light curves of Observations A1–P6 show no eclipses. From Kepler’s law and the ratio of the secondary radius to the binary separation (Eggleton 1983), the secondary has an angular radius of ~ 15°; hence the inclination ≤75°. We see from Fig. 6 that the disc warp does not deviate from the plane of the disc by more than 11° in our simulations, suggesting that the observed dips are likely to evolve on the disc-precession period.

7 CONCLUSIONS

We have analysed three new XMM–Newton observations of the M31 dipping LMXB Bo 158, in addition to re-analysing the three observations discussed in Trudolyubov et al. (2002). The newer observations spanned ~3 d in 2004 July. We find that the relationship between source intensity and depth of dipping is not simple, as described by Trudolyubov et al. (2002). Instead, we believe that the observed variation in dipping behaviour is caused by precession in the accretion disc; dipping would be confined to a limited phase range in the disc precession cycle.

We modelled the accretion disc with 3D SPH, and found prograde disc precession on a 81 ± 3-h period, as well as radiatively driven disc warp that precessed on a 31-h period in a retrograde fashion. We find that this disc precession is most likely to affect the observed dipping behaviour. Hence, we predict that the dipping behaviour of Bo 158 experiences a 81 ± 3-h cycle; this period is consistent with the observed variation of the dips.

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