**SWIFT REVEALS A ~5.7 DAY SUPER-ORBITAL PERIOD IN THE M31 GLOBULAR CLUSTER X-RAY BINARY XB158**

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Received 2014 August 19; accepted 2015 January 8; published 2015 March 4

**ABSTRACT**

The M31 globular cluster X-ray binary XB158 (a.k.a. Bo 158) exhibits intensity dips on a 2.78 hr period in some observations, but not others. The short period suggests a low mass ratio, and an asymmetric, precessing disk due to additional tidal torques from the donor star since the disk crosses the 3:1 resonance. Previous theoretical three-dimensional smoothed particle hydrodynamical modeling suggested a super-orbital disk precession period 29 ± 1 times the orbital period, i.e., ~81 ± 3 hr. We conducted a Swift monitoring campaign of 30 observations over ~1 month in order to search for evidence of such a super-orbital period. Fitting the 0.3–10 keV Swift X-Ray Telescope luminosity light curve with a sinusoid yielded a period of 5.65 ± 0.05 days, and a >5σ improvement in \(\chi^2\) over the best fit constant intensity model. A Lomb–Scargle periodogram revealed that periods of 5.4–5.8 days were detected at a >3σ level, with a peak at 5.6 days. We consider this strong evidence for a 5.65 day super-orbital period, ~70% longer than the predicted period. The 0.3–10 keV luminosity varied by a factor of ~5, consistent with variations seen in long-term monitoring from *Chandra*. We conclude that other X-ray binaries exhibiting similar long-term behavior are likely to also be X-ray binaries with low mass ratios and super-orbital periods.

**Key words:** X-rays: binaries – X-rays: general

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1. **INTRODUCTION**

The M31 globular cluster (GC) B158 (a.k.a. Bo 158), named following the Revised Bologna Catalogue v3.4 (Galleti et al. 2004, 2006, 2007, 2009), contains a bright X-ray source that was discovered by the Einstein observatory (Trinchieri & Fabbiano 1991), and has shown up in every X-ray observation of the region since; we call this X-ray source XB158.

XB158 exhibited strong intensity modulation on a 10017 ± 50 s (~2.78 hr) period during the 2002 January *XMM-Newton* observation (Trudolyubov et al. 2002). Trudolyubov et al. (2002) found similar variation in the folded light curves from a 1991 June *ROSAT* observation and a 2000 June *XMM-Newton* observation; they found that the amplitude of modulation decreased with increasing source intensity. They found no such modulation in the 2001 June *XMM-Newton* observation, setting a 2σ upper limit of 10% modulation. Assuming that this represents the orbital period, Trudolyubov et al. (2002) found that this is probably a neutron star binary with a low mass donor with a separation <10\(^{11}\) cm (i.e., a low mass XB-ray binary, LMXB).

However, analysis of the unfolded 2000 June *XMM-Newton* light curve revealed a single deep dip at the end of the observation, with no evidence for dips in the two previous orbital cycles (Barnard et al. 2006). Furthermore, Barnard et al. (2006) analyzed three proprietary *XMM-Newton* observations over 2004 July 17–19, finding ~100% dipping for one orbital cycle, and zero evidence for dips in other cycles; we concluded that the disk was precessing, with dips only visible for some part of the super-orbital cycle.

Such behavior is associated with the “superhump” phenomenon that is observed in accreting binaries where the mass ratio is smaller than ~0.3 (Whitehurst & King 1991). Superhumps were first identified in the superoutbursts of the SU UMa subclass of cataclysmic variables (CVs, accreting white dwarf binaries), manifesting as a periodic increase in the optical brightness on a period that is slightly longer than the orbital period (Vogt 1974; Warner 1975). SU UMs are a subclass of dwarf novae with orbital periods \(\gtrsim 2\) hr, that exhibit occasional superoutbursts that last \(\gtrsim 5\) times as long as the normal outbursts (Vogt 1980).

Osaki (1989) proposed that these superoutbursts are enhanced by a tidal instability that occurs when the outer disk crosses the 3:1 resonance with the secondary; the additional tidal torque causes the disk to elongate and precess, and also greatly enhances the loss of angular momentum (and therefore the accretion rate). The disk precession is prograde in the rest frame, and the secondary repeats its motion with respect to the disk on the beat period between the orbital period and the precession period, a few percent longer than the orbital period. The secondary modulates the disk’s viscous dissipation on this period, giving rise to the maxima in the optical light curve known as superhumps. Some short period, persistently bright CVs exhibit permanent superhumps (Paterson 1999; Retter & Naylor 2000). 4U 1916–053 is a high inclination neutron star LMXB with an X-ray period of 50.00 ± 0.08 minutes and an optical period of 50.458 ± 0.003 minutes (Callanan et al. 1995). It exhibits periodic X-ray intensity dips due to absorption by material in the outer disk; the amplitude of these dips varies over ~0% to ~100% on a ~4 day period, the precession period of the disk (Church et al. 1997; Chou et al. 2001). Haswell et al. (2001) showed that NS LMXBs with orbital periods shorter than ~4.2 hr are likely to exhibit superhumps, and identified 4U 1916–053 as a persistent superhumping source. XB158 appears to be somewhat analogous to 4U 1916–053 (Barnard et al. 2006).

In Barnard et al. (2006) we modeled the 2004 July 17 *XMM-Newton* pn spectrum of XB158 with a blackbody and a power law, finding \(kT = 2.0 ± 0.2\) keV, the photon index \(\Gamma = 2.0 ± 0.3\), \(\chi^2/\text{dof} = 19/19\), and the 0.3–10 keV luminosity was \(1.5 ± 0.6 \times 10^{38}\) erg s\(^{-1}\); fitting a single power law emission model yielded a photon index of 0.57 ± 0.09, which is harder than any black hole spectrum (Remillard & McClintock 2006), meaning that the
For each observation, we placed circular regions around XB158 and a suitable background region. We obtained the net source counts using the “Counts in regions” tool in the DS9 image viewer, and estimated the intensity by dividing the net counts by the exposure time. These data were obtained in order to determine the extent to which the varying off-axis angles affected our results.

We also created spectra from the same extraction regions, created appropriate ancillary response files using XRTMKARF, and found the appropriate response file using the QUZCIF tool. None of the spectra were suitable for free spectral fitting, hence we obtained luminosity estimates by assuming a model obtained from previous observations. For Chandra ACIS observations with >200 net source photons, the mean line-of-sight absorption (N\textsubscript{H}) was $9.4 \pm 1.0 \times 10^{20}$ atom cm\textsuperscript{-2} ($\chi^2$/dof = 7/11), and the mean power law index (Γ) was $0.52 \pm 0.02$ ($\chi^2$/dof = 5/11). This is consistent with the best absorbed power law fit to the 2004 July 17 XMM-Newton observation ($N_H = 0.1$, $\Gamma = 0.57 \pm 0.09$, $\chi^2$/dof = 30/24; Barnard et al. 2006). As we noted earlier, that XMM-Newton spectrum was best described by a blackbody + power law model, but neither the Chandra nor Swift spectra were sufficient to constrain the two-component emission model.

However, we were able to estimate the luminosity for each observation by assuming a fixed emission model, allowing only the normalization to vary. We fitted each spectrum using XSPEC 12.8.2b, fixing $N_H = 9.4 \times 10^{20}$ atom cm\textsuperscript{-2} and $\Gamma = 0.52$, to find the normalization required to make absorbed model intensity 1.00 count s\textsuperscript{-1}. We then calculated the unabsorbed flux for this model, allowing us to convert from intensity to flux. Multiplying the conversion by the background-subtracted intensity provided by XSPEC yielded the instrument-corrected, background-subtracted source flux. The luminosity was calculated from the flux assuming a distance of 780 kpc (Stanek & Garnavich 1998).

We fitted the light curve with constant and sinusoidal components using the QDP program provided in HEATOLLS, performing a simple search for periodicity. Scargle (1982) created a periodogram suitable for unbinned data with a mean of zero that produces exactly equivalent results to such least-squares fitting of sinewaves, but also allows comparison of the best period with other periods. The likelihood that any peak in the periodogram is real is given by the false alarm probability ($P$), where a low value of $P$ indicates that the peak is likely to be significant. If the highest frequency to be probed is $N$ times higher than the lowest frequency, then the power, $\mathcal{P}$, required for a false alarm probability $P$ is given by $\mathcal{P} = -\ln[1 - (1 - P)^{1/N}]$; for small $P$, $\mathcal{P} \sim \ln(N/P)$ (Scargle 1982).

3. RESULTS

We present our 30 day, 0.3–10 keV Swift XRT light curve of XB158 in Figure 1. We see that the 0.3–10 keV luminosity varied by a factor of $\sim$5; the luminosity dropped from $\sim2.3 \times 10^{39}$ erg s\textsuperscript{-1} to $\sim5 \times 10^{39}$ erg s\textsuperscript{-1} in ~2 days, assuming the mean Chandra absorbed power law model. We note that these Swift observations are non-contiguous, spacing the 2.5 ks observing time over several hours; the low intensities ($\sim$0.005–0.025 count s\textsuperscript{-1}) meant that there was no appreciable variability within each observation.

We find no evidence for a dependence of luminosity on off-axis angle; the luminosities for the observations when XB158 have the largest and smallest off-axis angles have consistent
values, while observations at an off-axis angle of 8.2' resulted in a factor of ~5 range in luminosity. The conversion factor for translating 1 count s⁻¹ into 0.3–10 keV flux ranged over 1.09–1.29 × 10⁻¹⁰ erg cm⁻² count⁻¹ for all observations except the second one, where it was 1.79 × 10⁻¹⁰ erg cm⁻² count⁻¹. This ~10% variation about the mean in instrumental correction is clearly not sufficient to account for the factor of ~5 variation in luminosity.

Fitting our light curve with a constant intensity yielded a best fit luminosity of ~1.3 × 10³⁸ erg s⁻¹, with χ² = 181 for 29 degrees of freedom (dof). However, adding a sinusoidal variation component yielded a much improved fit, with χ²/dof = 43/26; for this model, the period is 5.65 ± 0.05 days, with an amplitude of 7.1 ± 0.6 × 10³⁷ erg s⁻¹ around a mean luminosity of 1.43 ± 0.04 × 10³⁸ erg s⁻¹, and a phase of 88.1 ± 0.7 deg. All uncertainties in this work are quoted at the 1σ level.

This sinusoidal variability yielded Δχ² = 138 for 30 bins, with three extra free parameters; F-testing showed that the probability for this improvement being due to chance was 3 × 10⁻⁸, equivalent to a >5σ detection. In Figure 2 we show our Swift light curve folded on a 5.65 day period and fitted with the best fit sinusoid.

We present our Lomb–Scargle periodogram for the 0.3–10 keV Swift XRT luminosity light curve of XB158 in Figure 3, and also indicate the power required for false alarm probabilities P = 0.5, 0.05, and 0.005 for reference. We tested 30 frequencies, and oversampled each frequency by a factor of 50; this resulted in a periodogram covering a wider range of periods than is interesting (up to ~1500 days), so we show only part of the periodogram here. The periodogram shows a single strong peak, with the maximum power of 10.4 at a period of 5.60 days, corresponding to P = 0.0009; the range of periods which are detected at a >3σ level is 5.4–5.8 days. While there is a small peak at the 3 day period, P = 1 for this peak.

4. DISCUSSION AND CONCLUSIONS

XB158 is a high inclination X-ray binary associated with the M31 GC B158. It exhibits deep intensity dips on a 2.78 hr period in some observations but not others, prompting Barnard et al. (2006) to suggest that the disk is precessing, caused by the “superhumping” phenomenon observed in low mass ratio systems where the disk crosses the 3:1 resonance with the donor star.

Barnard et al. (2006) predicted a disk precession period of 29 ± 1 times the orbital period, i.e., 81 ± 3 hr, inspiring a month of daily monitoring of the M31 central region by Swift. Fitting a sinusoid to the light curve revealed a 5.65 ± 0.05 day superorbital period (1σ uncertainties); the 0.3–10 keV luminosity varied by a factor of ~5, which is consistent with the range of luminosities observed in the ACIS observations of our 13+ yr Chandra monitoring campaign (Barnard et al. 2012).

The peak of the Lomb–Scargle periodogram is at 5.6 days, consistent with that obtained from least squares fitting of the light curve with a sinusoid. The suggested super-orbital period is ~70% longer than predicted by our 3D SPH simulations (Barnard et al. 2006). None of the authors of the current paper are experts in SPH; however, J. R. Murray stated in a private communication (2014) that the longer than expected superorbital period is likely due to the mass ratio of the donor to the accretor being lower than assumed. The mass of a Roche lobe filling main sequence star, m, may be approximated as m ≃ 0.11 P₉₉ hr, where P₉₉ is the orbital period in hours (Frank et al. 2002), and we originally assumed a donor mass of ~0.30 M⊙. For the accretor, we assumed a 1.4 M⊙ neutron star. A power law
emission model fit to the 2004 July 16 XMM-Newton spectrum of B158 yielded a photon index of 0.57 ± 0.09 (Barnard et al. 2006), which is considerably harder than any spectrum emitted by a black hole binary. However, some neutron stars have masses > 2 $M_\odot$ (see, e.g., Demorest et al. 2010; Lynch et al. 2013), and it is possible that XB158 contains a particularly massive neutron star.

We noted in Barnard et al. (2012) that other XBs such as XB146 exhibited strong luminosity fluctuations between fairly consistent maxima and minima during our Chandra monitoring observations, and suggested that this long-term behavior could be indicative of a short period/low mass ratio system. Our new findings support this hypothesis.

We thank the anonymous referees for suggesting improvements to this work, in particular for prompting a more rigorous estimation of the super-orbital period. We thank the Swift team for making this work possible. This work was funded by Swift grant NNX13AJ76G.

Facility: Swift (XRT)

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