Finding Periods in High Mass X-Ray Binaries

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Abstract This is a call for amateur astronomers who have the equipment and experience for producing high quality photometry to contribute to a program of finding periods in the optical light curves of high mass X-ray binaries (HMXB). HMXBs are binary stars in which the lighter star is a neutron star or a black hole and the more massive star is a Type O supergiant or a Be type main sequence star. Matter is transferred from the ordinary star to the compact object and X-rays are produced as the the gravitational energy of the accreting gas is converted into light. HMXBs are very bright, many are brighter than 10th magnitude, and so make perfect targets for experienced amateur astronomers with photometry capable CCD equipment coupled with almost any size telescope.

1. Introduction

The brightest class of X-ray sources in the sky are the X-ray binaries (White *et al.* 1995). As such, they were among the first X-ray objects to be studied when sounding rockets and balloon flights first carried X-ray detectors above the Earth's atmosphere in the 1960s (Begelman and Rees 1998). X-ray binaries consist of a neutron star or black hole accreting material from a massive companion star. The two main classes of X-ray binaries are high mass X-ray binaries (HMXBs) and low mass X-ray binaries (LMXBs), with the difference being defined by whether the companion star is of higher mass or of lower mass than the accreting neutron star or black hole.

Low mass X-ray binaries are similar to the cataclysmic variables (CVs) that many AAVSO members observe nightly, except that a white dwarf, and not a neutron star or black hole, is accreting matter from the companion star in the case of a CV.

The companion star for both CVs and LMXBs are generally dim main sequence M or K stars. CVs tend to be brighter than LMXBs because their accretion disks are brighter at optical wavelengths. LMXBs are dim blue objects, optically, with magnitudes typically in the high teens and fainter.

High mass X-ray binaries, on the other hand, tend to be bright (γ Cas is one!) because the companion stars are bright O or B spectral type stars. Early-type O and B stars have lifetimes of only a few million years on the main sequence, so HMXBs are young objects in which one member of the binary has already gone supernova. The current generation of stars (population I) were formed from gas clouds within the disk of the Milky Way galaxy. Since the HMXBs are young members of the current generation, they have not yet had time to move far from their birth place in the galactic disk and so are found within the Milky Way on the sky. There are also HMXB sources accessible to amateur astronomers in the Magellanic Clouds with magnitudes in the 12 to 14 range.

This paper is a call for interested amateur astronomers to participate in a project to find periods in the light curves of HMXBs. Only 47 of the 130 known HMXBs have known periods (Liu, van Paradijs and van den Heuvel 2000, hereafter LPH; Bosch-Ramon *et al.* 2005). These known periods correspond to orbital periods, but it is entirely possible that other periods such a star rotation rate could be found. Many of the orbital periods could be a year or two in length making this a long-term project. In the rest of this paper we will review a little of what is currently known about HMXBs, give a list of objects with unknown periods, and give some direction about how to become involved in the project.

2. What are HMXBs?

There are two broad classes of HMXBs (see Figure 1). Those are the short period ones (a few days) with O- or early B-type supergiant companions (SG/X-ray binary) and longer period ones (from several weeks to several years) with type B companions (Be/X-ray binary) (Verbunt and van den Heuvel 1995). The majority of known systems are Be/X-ray binaries. Both types of HMXBs are thought to have had one or more episodes of mass transfer between the two original stars before one of them exploded as a type Ib supernova (helium star core collapse, all the hydrogen would have been transferred to the companion).

In the case of a short period SG/X-ray binary, also known as a "standard" HMXB, the supernova progenitor is theorized in most cases to have swollen in diameter to completely engulf the other star and a spiral-in phase, similar to that hypothesized for CVs, brought the core of the imminent supernova into a short period orbit with its companion. After the supernova, the short period SG/X-ray binaries, as we now observe them, transfer mass from the now evolved type O supergiant companion to the neutron star or black hole supernova remnant. The type O supergiant will have a mass greater than 15M . The companion star will fill or nearly fill its Roche lobe and the mass transfer rates will be high enough to produce a permanently bright X-ray binary. The famous Cygnus X-1 is a SG/X-ray binary that fills its Roche lobe with an orbital period of 5.6 days. Continued evolution (which is relatively fast because of the high mass transfer rate in a shrinking orbit) and expansion of the companion will lead to a second spiral-in phase with the roles of the two stars now reversed. The companion will go supernova in its turn, leaving a binary neutron star or a neutron star and a black hole. Through the emission of gravitational radiation, that exotic binary will eventually merge to produce a short duration gamma-ray burst (Gehrels *et al.* 2005). Some short period HMXBs exhibit relativistic jet outflow as a result of the mass transfer. When jets are present, the HMXB is commonly referred to as a microquasar because it is, in many ways, a miniature version of a quasar at the heart of some active galactic nuclei (AGN) (Wu *et al.* 2002).

In the case of a long period Be/X-ray binary, the original orbit was wide enough to prevent a spiral-in phase before the first supernova. In that case no mass or angular momentum was lost from the system and the mass transfer eventually caused the orbit to widen even further. The sideways kick of the supernova also caused the current orbit to be highly eccentric. The companion star will generally be a rapidly rotating Be (e for 'emission' spectrum) star. The massive B star, with a mass between 8 and 15M , loses much mass through its stellar wind and also through an equatorial disk caused by the star's rapid rotation. The equatorial disk is the source of the emission lines in the star's spectrum. Gas lost through both mechanisms will accrete onto the neutron star or black hole to produce X-rays. Occasional increases in mass flow from the equatorial bulge can lead to very bright X-ray transients. Also, mass transfer and the system's brightness will increase as the neutron star or black hole passes periastron. In fact, many Be/X-ray binaries are generally visible in the X-ray, as X-ray transients, only during periastron passage. The originally closer Be/X-ray binaries will evolve to a merger after the Be star moves off the main sequence, fills its Roche lobe, and spirals in toward the compact star. Originally wider Be/X-ray binaries will evolve into binary radio pulsars (Verbunt and van der Heuvel 1995) like the famous gravitational wave emitting Hulse-Taylor pulsar. The gravitational radiation will cause the radio pulsar eventually also to merge in a short duration gamma-ray burst.

In searching for periods in HMXBs we primarily expect to find orbital periods. But finding other periods, such as the spin rate of the compact star, is also a possibility, especially if the compact star turns out to be a white dwarf (WD). A system containing a white dwarf would not be an SG or Be X-ray binary but would be a completely different kind of object, one intermediate between a CV and the standard HMXB. X-ray systems with white dwarfs are thought to be in a permanent nova situation, with continuous nuclear fusion on the surface of the WD of the accreted gas, and are thought to be associated with objects having an extreme ultra-soft (EUS) X-ray spectrum (also known as "super-soft" X-ray sources (Hellier 2001)). HMXB-like systems that turn out to have white dwarfs instead of neutron stars or black holes also exist; an example is γ Cas.

Orbital motion can cause periodic variation in a HMXB light curve in a number of ways. For a short period SG/X-ray binary that fills or nearly fills its Roche lobe, there will be "ellipsoidal variation" caused by the changing projected area of the star as seen from Earth. For the short period binaries, and even for longer period binaries with a sufficiently massive black hole (Copperwheat *et al.* 2005), irradiative heating of the companion star by X-rays from the accretion disk around the compact star can cause light curve variation as the brighter heated side of the star becomes visible and hidden in the course of the orbit. Finally, the increased accretion rate caused by the passage of the compact star through periastron around the Be star can cause a brightening in the light curve.

HMXBs tend to be relatively active objects and other effects can give rise to variability in the optical light curve. Optically, most of the light comes from the O or B star. In the X-ray region of the electromagnetic spectrum the light comes from the accretion disk and accretion layer on the surface of neutron star. The X-ray spectrum from the accretion layer is hard (bright at high energies) while the X-ray spectrum from the inner disk is soft (bright at lower energies). So the absence of a hard X-ray spectra can be evidence for a black hole because a black hole has no surface and hence no accretion layer. In any case, variation of accretion rate will cause variation in X-ray brightness which, in turn, will cause variation in optical light produced by the "reprocessing" of the X-ray radiation in either the accretion disk or in the atmosphere of the companion star. Variations in the accretion rate can be quite dramatic if the accretion rate is large enough to produce radiation at the "Eddington limit." If the accretion is at the Eddington limit, pressure from the emitted light radiation will be high enough to push the accreting gas away and shut off the mass flow. With the mass flow cut off, the disk and accretion layer luminosity then falls below the Eddington limit and mass flow starts again. If the system possesses a jet then more complicated behavior is possible and wide variability in the X-ray light curve is common (Muno *et al.* 1999), which may or may not translate into optical variability. These other sources of variability may make it difficult to extract the period from some of the HMXB light curves.

3. List of targets

Table 1 gives a list of our HMXB program stars. They are the objects listed by LPH that have unknown orbital periods and known optical counterparts. There are forty-seven program stars. Nine are listed as type O , which are likely to have short orbital periods (days), thirty-six are listed as type B, which are likely to have long periods (up to one or two years), and two are of unspecified type.

The columns in Table 1 give information as follows. The first column gives the entry number in order of appearance in the LPH catalogue. The second column gives the name of the object as given in the LPH catalogue. Most objects have several names and will be given Harvard designations by the AAVSO as data are posted to the AAVSO International Database. The third column gives the *V*-magnitude of the optical counterpart (the O or B star) of the X-ray binary. The fourth column gives the spectral type. For those objects that are X-ray pulsars, the sixth column gives the pulse period. The fifth column gives the type, P, T, or U, which means:

• P: X-ray pulsar. X-ray pulsars are the X-ray binary analogue of CV polars. They have high magnetic fields that channel the flow onto one or two hot spots on the surface of a neutron star. As can be seen, the pulse periods generally imply a neutron star spin rate that is far too rapid to be detectable by photometric exposures that last tens of seconds. But the possibility of detecting the longer period spin rates by photometry remains.

• T: transient X-ray source. These are mostly type B objects, as expected, but four of the transient sources have O companions; however, of those four, three are emission objects suggesting equatorial mass loss.

• U: ultra-soft X-ray spectrum. These sources are black hole candidates, or if the X-ray spectrum is "extreme ultra-soft" (EUS) the accreting object may be a white dwarf in which the accretion rate is high enough to support nuclear fusion—a permanent nova.

Here are some notes on the individual objects as given in LPH:

LPH001: Small Magellanic Cloud (SMC) object.
LPH004: SMC object as well, SMC X-3, $\upsilon_{rot} \sin i \sim 200$ km s^{-1}.
LPH008: SMC 25.
LPH009: In SMC.
LPH010: SMC 32.
LPH011: SMC X-2, $\upsilon_{rot} \sin i \sim 200$ km s^{-1}.
LPH012: γ Cas, variable Be star, possibly WD sys., $\upsilon_{rot} \sin i \sim 300$–$500$ kms^{-1}.
LPH017: In SMC.
LPH018: In SMC, EUS object.
LPH020: In SMC, consistent with supernova remnant SNR 0101-724.
LPH021: In SMC.
LPH023: In SMC, consistent with supernova remnant SNR 0104-72.3.
LPH024: In SMC, displays optical outbursts.
LPH028: In SMC, black hole candidate, rotational velocity 145 km s^{-1}.
LPH029: In open cluster NGC 663, $\upsilon_{rot} \sin i \sim 250$ km s^{-1}.
LPH033: CI Cam, possible BH candidate, possible symbiotic-type X-ray binary.
LPH035: In Large Magellanic Cloud (LMC).
LPH036: In LMC.
LPH038: In LMC.
LPH039: In LMC.
LPH046: In LMC, black hole candidate.
LPH053: In LMC.
LPH054: In LMC.
LPH055: In LMC, optical identification not completely certain.

LPH056: In LMC.
LPH058: Possibly the GeV gamma-ray source 2EG J0635+0521.
LPH062: In open cluster NGC 2516.
LPH067: Possible Wolf-Rayet star + O star rather than a HMXB.
LPH069: Probably the same as LPH068.
LPH071: $\upsilon_{rot} \sin i \sim 300$ km s^{-1}.
LPH079: Possible white dwarf accretor.
LPH080: Possible white dwarf accretor.
LPH100: A γ-ray emitting persistent microquasar.
LPH129: Herbig Ae/Be candidate.

The high rotational velocities of LPH004, 011, 012, 028, 029, and 071 fit with their B-emission type character, as B-emission stars always are very rapid rotators. Such systems are expected to have long orbital periods: several weeks to several years. The period of LS 5039/RXJ1826.2-1450 (LPH100) has been found to be 3.9060 ± 0.0002 days (Bosch-Ramon *et al.* 2005) but we are keeping it on our list because its light curve to date has shown no significant variation; its period was found spectroscopically. At high enough precision, there may be some structure to the light curve at optical wavelengths, and variations of ~0.4 magnitude have been reported in the *H* and *K* infrared bands (Clark *et al.* 2001).

4. Observing methods

The amplitudes of the light curves may be very small so it may be necessary to observe with a precision to 0.005 magnitude or better. However, at this point we simply do not know what the amplitude of the variations will be, so more standard data with 1% or so errors (0.01 magnitude) will also be very useful. The finer requirement is similar to the precision needed to detect the transits of extrasolar planets, so the same equipment and observing techniques required for observing extrasolar planet transits can be used to observe HMXBs. An excellent overview of the equipment and observing techniques required to achieve 0.005 magnitude precision is given by Castellano *et al.* (2004). The HMXBs generally will need to be observed through the standard Johnston *B*, *V*, *R*, and *I* filters so that we can easily combine data from different observers and so we can see if any variable color effects are present. But, again, *V*-band only observations, for example, will also be very useful.

We will be organizing the observing efforts into campaigns using the AAVSO photometry e-mail list. The idea is to get nearly continuous coverage of the HMXB's light curve with what might be called an "Amateur Astronomers' Whole-Earth Telescope" or AAWET. Observers at all longitudes would provide continuous coverage for a month or so similar to how nearly continuous coverage was obtained in a recent AAVSO project on SS Cygni. Also in a manner similar to the way in which the SS Cyg campaign was run, observers would reduce their data and post to the AAVSO International Database in the usual manner. We would also request that observers reduce a few check stars in their frames because the light curves of those check stars will be necessary to verify any unusual activity seen in the HMXB's light curve. The check star data won't be submitted to the AAVSO database but should be archived by the observer in case the data are needed. Charts showing the field and preferred check stars will be made available to the observers when a campaign starts.

Once a long enough light curve is produced, it will be subject to a period analysis using standard software such as PERANSO (Vanmunster 2005). Continuous coverage at a reasonably high time resolution will also allow us to search for short periods and to eliminate high frequency noise in the periodogram.

To date we have photometric data for LPH046, 053, 067, 069, 071, 088, 095, 100, 107, 115, 123, 127, 128, and 129. Thus, stars in that list will be our first campaign targets. These are the brighter stars in the list (brighter than magnitude ~14). Outside of the list of the stars already observed are the fainter ones, which will be tougher to observe with high precision, and stars that refuse to show simple light curves, like γ Cas. If you are interested in participating in this challenging project of finding periods for high mass X-ray binaries, keep a look out for observing requests on the AAVSO photometry e-mail list and Special Notices.

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Table 1. Program star list. See main text for notes.

LPH No.	*Name*	*V*	*Spectral Type*	*Type*	*Ppulse (sec)*
001	J0032.9–7348	15.3	Be		
004	0050–727	14. :	O9 III-Ve	T	
008	J0051.9–7311	14.4	Be	T	
009	J0052.1–7319	14.667	Be	TP	15.3
010	J0052.9–7158	15.46	Be	TU	
011	0053–739	16	B1.5Ve	T	
012	0053+604	1.6–3.0	B0.5Ve		
017	J0058.2–7231	15	Be		
018	J0059.2–7138	14.1	B1IIIe	TUP	2.7632
020	J0103–722	14.8	O9-B1(III-V)	P	345.2
021	0103–762	17	Be	T	
023	J0106.2–7205	16.7	B2-B5 III-Ve		
024	J0111.2–7317	15.32	B0-2III-Ve	TP	31.0294
028	J0117.6–7330	14.19	B0.5IIIe	TP	22.07
029	J0146.9+6121	11.33	B1Ve		1404.2
033	J0421+560	9.25	—	T	
034	J0440.9+4431	10.78	B0V-IIIe	P	202.5
035	J0501.6–7034	14.5	B0e		
036	J0502.9–6626	14.22	B0e	TP	4.0635
038	J0516.0–6916	15	B1e	T	
039	J0520.5–6932	14.4	O8e	T	
040	0521+373	7.51	B0IVpe		
046	J0532.5–6551	12.3	OB	U	
053	J0541.4–6936	12.01	B2 SG		
054	J0541.5–6833	14.02	OB0		
055	0544–665	15.4	B1Ve		
056	J0544.1–710	15.33	Be	TP	96.08
057	0556+286	9.2	B5ne		
058	J0635+0533	12.83	B2V-B1IIIe	P	0.0338
061	0739–529	7.62	B7IV-Ve		
062	0749–600	6.73	B8IIIe		
067	1024.0–5732	12.7	O5:	P	0.061

(Table 1 continued on following page)

Table 1. Program star list, continued.

LPH No.	*Name*	*V*	*Spectral Type*	*Type*	*Ppulse (sec)*
069	J1037.5–5647	11.3	B0V-IIIe	P	862
071	1118–615	12.1	O9.5 III-Ve	PT	405
079	1249–637	5.31	B0IIIe		
080	1253–761	6.49	B7Vne		
081	1255–567	5.17	B5Ve		
088	1555–552	8.6	B2nne		
095	J1744.7–2713	8.4	B2V-IIIe		
100	J1826.2–1450	11.23	O7V((f))		
107	1845.0–0433	13.96	O9.5I	T	
115	1936+541	9.8	Be		
117	1947+300	14.2	—	T	
123	J2030.5+4751	9.27	B0.5V-IIIe		
127	2202+501	8.8	Be		
128	2206+543	9.9	B1e		392. ?
129	2214+589	11	Be		

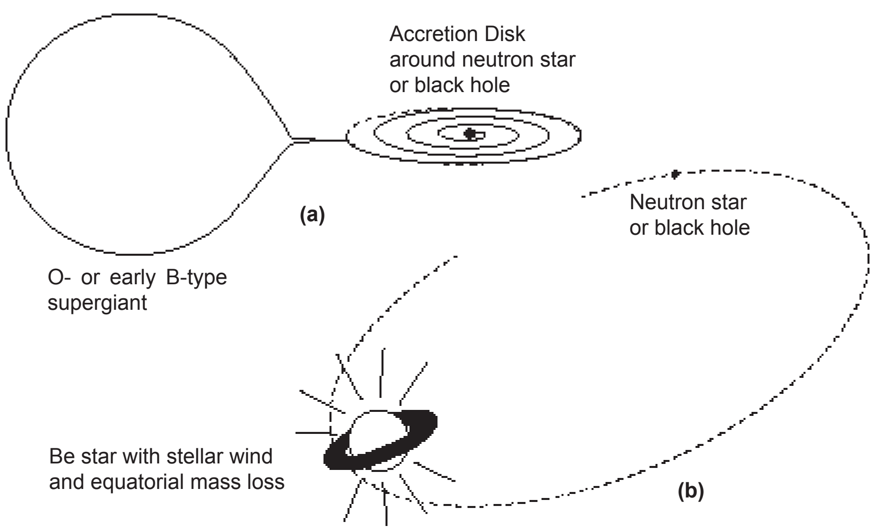

Figure 1. Schematics showing the two main types of high mass X-ray binaries. (a) A short period (days) SG/X-ray binary consisting of a supergiant O- or early-B type star filling or nearly filling its Roche lobe and transferring mass via an accretion disk to an orbiting neutron star or black hole. (b) A long period (several weeks to several years) Be/X-ray binary consisting of a Be rapidly rotating main sequence star that transfers mass to a neutron star or black hole in a highly eccentric orbit via mass loss through stellar wind and through a centrifugally produced equatorial disk.