AX J0049.4-7323 - a close look at a neutron star interacting with a circumstellar disk

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ABSTRACT
Detailed evidence on the system AX J0049.4-7323 is presented here to show how the passage of the neutron star in the binary system disrupts the circumstellar disk of the mass donor Be star. A similar effect is noted in three other Be/X-ray binary systems. Together the observational data should provide valuable tools for modelling these complex interactions.

1 INTRODUCTION AND BACKGROUND
The Be/X-ray systems represent the largest sub-class of massive X-ray binaries. A survey of the literature reveals that of 96 proposed massive X-ray binary pulsar systems, 57% of the identified systems fall within this class of binary. The orbit of the Be or supergiant star and the compact object, presumably a neutron star, is generally wide and eccentric. X-ray outbursts are normally associated with the passage of the neutron star close to the circumstellar disk (Okazaki & Negueruela, 2001). A recent review of these systems may be found in Coe (2000).

The optical light from a Be/X-ray binary is dominated by the mass donor star in the blue end of the spectrum, but at the red end there is a significant contribution from the circumstellar disk. Long term optical observations such as those collected by the MACHO experiment (Alcock et al, 1995) provide valuable insights into the behaviour of the circumstellar disk, and hence into some of the details of the binary interactions within the system.

2 AX J0049.4-7323
2.1 Optical and X-ray outbursts
The optical counterpart to AX J0049.4-7323 (Yokogawa et al, 2000) was identified by Edge & Coe (2003) as V=15 Be star. Subsequently Cowley & Schmidtke (2003) analysed the long term light curve of this object obtained from the MACHO data base. They showed that the optical object exhibited outbursts every 394d which they proposed to be the binary period of the system. Furthermore they also showed the presence of a quasi-periodic modulation with a period ~11d which they associated with the rotation of the Be star’s disk.

The MACHO red band data are reproduced in the top panel of Figure 1 for a period of approximately 4 years. The outbursts reported by Cowley & Schmidtke (2003) are very clear at the interval of 394d. From the timing of the outbursts one can define a ephemeris of:

T_{outburst} = JD2449830 + 394N

These epochs of visible outbursts are marked on Figure 1 with the “V” symbol.

The X-ray source has certainly been detected 5 times to date, 3 times by the ASCA satellite observatory (Yokogawa et al, 2000) and twice by the Rossi XTE spacecraft (Laycock et al, 2003). The two RXTE detections are indicated on Figure 1 by an “X” symbol. The phase of these two detections is exactly synchronised with the above ephemeris derived from the optical outbursts. Therefore there can be no further doubt that this period of 394d represents the binary period of the system, with X-ray outbursts synchronised with the periastron passage of the neutron star (NS). However, the ASCA X-ray outbursts are harder to integrate into this model. They are indicated on Figure 1 by “A” symbols. It is immediately clear that the ASCA X-ray outbursts have occurred at different times to the MACHO/RXTE ephemeris and raises the question as to whether it could be a different source entirely (see Discussion).

2.2 The ~11d modulation
The reported ~11d modulation in the MACHO data for AX J0049.4-7323 was investigated in detail here. Cowley & Schmidtke (2003) suggest that this arises from the interaction of the NS with the circumstellar disk of the Be star. The MACHO data were analysed in moving blocks of 80d to see how the period and amplitude varied over the whole data set. Each block of 80d was subjected to a Lomb-Scargle analysis and the position and amplitude of the highest peak in the power spectrum determined. The data sample was then moved on by 1d and the process repeated. The results are presented in the lower two panels of Figure 1 (each 80d block result is displayed at the mid point of the time interval being investigated). From this it can immediately be seen that there is a strong increase in the pulse amplitude.
Figure 1. Top panel: the MACHO red lightcurve for the system AX J0049.4-7323 over approximately 4 years. The “V” symbols indicate the phase of the optical outbursts, the “X” symbol the epoch of the RXTE outbursts and the “A” symbols the epoch of X-ray outbursts seen by ASCA (see text for references). Centre panel: the measured period of the modulation determined by studying a moving sample of length 80 days. Bottom panel: the amplitude of the modulation using the same time bins as in the central panel. The amplitude corresponds to the magnitude of the most significant peak in the power spectrum.
Figure 2. Two examples of the Lomb-Scargle power spectrum obtained from individual 80d samples. The upper example shows one of the periods in which the ∼11d period is very strong. The lower curve shows one of the less frequent intervals in which the power spectrum becomes more complex and other frequencies share the power.

associated with the 394d cycle peaking at optical outburst. Furthermore, the modulation period is also often substantially disturbed at the same epochs. The occasional points at 6-7d represent times when the power spectrum becomes more complex - see Figure 2 for two examples of the power spectra from individual 80d samples.

3 OTHER SIMILAR SYSTEMS

The observed optical modulation in AX J0049.4-7323 is not unique in the published literature. There are at least three further systems in which a similar optical modulation is observed. These are listed in Table 1.

In each case the MACHO lightcurve in the red band was extracted from the archive and the data folded at the binary period. The resulting folded lightcurves are presented in Figure 3.

The lightcurves are all very asymmetric, and show strong evidence for a sharp rise followed by a slower decline. This effect is clear in all the lightcurves shown, even though the binary periods range from 394d to 16d (AX J0049.4-7323 to A0538-66).

4 DISCUSSION

4.1 Does AX J0049.4-7323 = XTE J0049-723?

The probable association of the ASCA X-ray source with the MACHO/RXTE X-ray source seems quite high. The ASCA error circle (illustrated in Figure 1 of Edge & Coe, 2003) has a radius of ∼1 arcmin and includes the MACHO object (albeit just inside the Eastern edge). In addition, the reported ASCA pulse period of 755.5s is very close to the RXTE period of 751s.

The pulsar spin rate between the last ASCA detection and the first RXTE detection some 5 months later can be used to estimate the average X-ray luminosity. Using Equation 6.16 from Frank, King & Raine (1992) one
can determine that such a change in spin rate over such a period of time requires an average X-ray luminosity of 
\[ L_x = 3 \times 10^{36} \text{ erg/s} \] using a value for \( \mu_{30} \) of 1. However, values of \( \mu_{30} \) in the range 0.1-10 produce results in the range 
\[ L_x = (0.1 - 4.0) \times 10^{36} \text{ erg/s} \]. Laycock et al (2003) estimate the detected X-ray luminosity in the outbursts to
be 
\[ L_x = 2 \times 10^{37} \text{ erg/s} \], whereas the ASCA detected luminosities are estimated by Yokogawa et al (2000) to be only
\[ L_x = 5 \times 10^{35} \text{ erg/s} \] (well below the RXTE detection threshold). Therefore depending upon the correct value of \( \mu_{30} \) it could well be possible for the pulsar to have spun up over the \( \sim 5 \) months. Laycock et al (2003) carried out eight RXTE observations of the SMC which included (but did not detect) this source between the last ASCA detection and the first RXTE detection. However, the source may well have been just below its sensitivity limit.

The timing of the ASCA X-ray outbursts presents a puzzle. They do not coincide with the phase of the optical and XTE outbursts. For these kind of systems one normally sees two kinds of X-ray outbursts:

- Type I outbursts associated with the periastron passage of the NS through the circumstellar disk

- Type II which occur randomly in the binary phase and are thought to be associated with an unusually large mass ejection event from the mass donor star. They often last in excess of a binary orbit implying that the mass outflow is flooding the entire orbital space.

Not surprisingly, Type II outbursts are normally substantially more X-ray luminous than Type I. The ASCA outbursts reported by Yokogawa et al (2000) do not fit into either category - they are not at the right phase for Type I, nor are they bright enough and long enough for Type II. The intervals between the ASCA outbursts are 544d and 336d. Therefore the only other possibility is that the source spent an extended period of time showing persistent, low-level X-ray emission similar to X Persei and other supergiant systems. However, there are no systems known to exhibit this mixture of persistent and outburst characteristics, so this is hard to understand.

Could the ASCA and RXTE objects be different systems but with a coincidentally similar pulse period? There is certainly the salutary example of 4U 1145-619 and 1E 1145-619, pulse periods of 292s and 297a respectively, and lying just 15 arcmin apart in the galaxy (Lamb et al, 1980). These objects caused much confusion with early spacecraft observations until it was realised they were two separate systems. In addition, in the case here of AX J0049.4-7323, Laycock et al (2003) point out that the reported pulse pro-

### Table 1. List of periods observed in the systems.

| Object Name | Pulse Period (s) | Orbital Period (d) | References |
|-------------|-----------------|-------------------|------------|
| AX J0049.4-7323 | 755 | 394 | Cowley & Schmidtke (2003) |
| A0538-66 | 0.069 | 16.6 | Alcock et al., 2001 |
| RX J0058.2-7231 | ? | 59 | Schmidtke, Cowley & Levenson, 2003 |
| RX J0520.5-6932 | ? | 24.5 | Coe et al, 2001 |

files between RXTE and ASCA are very different from each other. Perhaps only better observations with imaging X-ray telescopes will resolve this matter.

### 4.2 The \( \sim 11d \) modulation in AX J0049.4-7323

Both of the lower curves shown in Figure 1 strongly suggest the idea that the \( \sim 11d \) modulation is induced by the periastron passage of the NS. If the modulation amplitude is folded modulo the amplitude and phase of the binary modulation given in Section 2.1, then a strong regular pattern is revealed - see Figure 4. Interestingly there is little evidence to show the induced modulation systematically decreasing in the intervals between NS passages. On the contrary, there is some evidence in this figure for the amplitude building up over the \( \sim 180d \) prior to the optical outburst. The smaller spikes seen in the lower panel of Figure 1 at different phases than the outburst phase can be seen contributing to the average curve shown in Figure 3 around phases 0.6-0.8. All this activity well before phases 0.0 strongly suggests that the disk feels the effect of the approaching NS long before the force becomes so strong that the disk can spill over from its previously confined configuration (and hence enhance the optical luminosity).

Similar psuedo periodic modulations have been reported by Schmidtke et al (2004) from MACHO data of 2-3 other Be/X-ray systems in the Magellanic Clouds. So this phenomenon may exist in many of these systems and comparison of the differences and similarities in the behaviour patterns may well prove extremely valuable in understanding the neutron star/circumstellar disk interactions.

### 4.3 The binary modulation lightcurve

The first obvious feature to note from these light curves is that they are not representative of the lightcurve one obtains from the extended envelope of a star in a tight binary system. Such a situation will produce a very sinusoidal modulation such as that seen in RX J0050.7-7316 and modelled by Coe & Orosz (2000).

Okazaki & Negueruela (2001) suggest that in these systems the circumstellar disk is truncated inside the periastron

![Figure 4. The amplitude of the \( \sim 11d \) modulation folded modulo the 394d binary period. Phase zero is defined in Section 2.1 as the time of peak optical outburst. The data are shown twice for clarity.](image-url)
separation, and hence the optical outburst would arise from
the previously stable configuration being disrupted at peri-
astraon. If this model is correct then the different profiles
may well represent differing inclination angles of the NS to
the circumstellar disk. Hence the relative rate of passage
past the disk would give rise to narrower or broader profiles
- an effect independent of the binary period. Interestingly,
the outburst profile is much sharper for the two systems with
known pulse periods (AX J0049.4-7323 and A 0538-66) than
the other two. This suggests a possible link between the sys-
tem orientation to the line of sight and our ability to see the
poles of the NS.

5 CONCLUSIONS
Detailed evidence on the system AX J0049.4-7323 has been
presented here to show how the passage of the neutron star
disrupts the circumstellar disk of the Be star. A similar ef-
fect is noted in three other Be/X-ray binary systems. To-
gether the observational data should provide valuable tools
for modelling these complex interactions.

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