Observations of the unusual counterpart to the X-ray pulsar AX J0051–733 *

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ABSTRACT

We report optical and IR observations of the ASCA X-ray pulsar system AX J0051-733. The relationship between the X-ray source and possible optical counterparts is discussed. Long term optical data from over 7 years are presented which reveal both a 1.4d modulation and an unusually rapid change in this possible binary period. Various models are discussed.

Key words: stars: emission-line, Be - star: binaries - infrared: stars - X-rays: stars - stars: pulsars

1 INTRODUCTION

High Mass X-ray binaries (HMXBs) are traditionally divided into Be/X-ray and supergiant binary systems. A survey of the literature reveals that of the 96 proposed massive X-ray binary pulsar systems, 67% of the identified systems fall within the Be/X-ray group of binaries. The orbit of the Be star and the compact object, a neutron star, is generally wide and eccentric. The optical star exhibits Hα line emission and continuum free-free emission (revealed as excess flux in the IR) from a disk of circumstellar gas. Most of the Be/X-ray sources are also very transient in the emission of X-rays.

The source that is the subject of this paper, AX J0051-733, lies in the Small Magellanic Cloud, a region of space that is extremely rich in HMXBs. It was reported as a 323s pulsar by Yokogawa & Koyama (1998) and Imanishi et al (1999). Subsequently Cook (1998) identified a 0.7d optically variable object within the ASCA X-ray error circle. The system was discussed in the context of it being a normal HMXB by Coe & Orosz (2000) who presented some early OGLE data on the object identified by Cook (1998) and modelled the system parameters. Coe & Orosz identified several problems with understanding this system, primarily that if it was a binary then its true period would be 1.4d and it would be an extremely compact system. In addition, the combination of the pulse period and such a binary period violates the Corbet relationship for such systems (Corbet, 1986).

In this paper we report on extensive new data sets from both OGLE and MACHO, as well as a detailed photometric study of the field. The results reveal many complex observational features that are hard to explain in the traditional Be/X-ray binary model.

2 X-RAY SOURCE LOCATION

As will be seen from the photometric results presented below, it is critical to establish the correct optical counterpart to the X-ray pulsar. In particular, it is vital to clearly link the ASCA source to an optical object, and other ROSAT X-ray sources may, or may not be relevant (because no pulsations have been detected from ROSAT objects). Figure illustrates the somewhat complex situation associated with this object. In this figure the large dotted circle indicates the original ASCA X-ray position and uncertainty from Imanishi et al (1999). Within this error circle lie the much smaller error circles of the ROSAT sources RX J0050.8-7316 (Cowley et al, 1997) and RX J0050.7-7316 (Kahabka 1998). Subsequently, the position of the ASCA error circle was refined to the large solid circle shown in the figure (Imanishi 2001, private communication).

Within the ROSAT error circle for RX J0050.7-7316 and the revised ASCA circle for AX J0051-733 lies an obvious optical object that has been proposed as the counterpart to both of these X-ray objects (Cowley et al, 1997, Schmidtke

* Partially based on observations collected at the South African Astronomical Observatory and the European Southern Observatory, Chile (ESO 65.H-0314)
512 is the proposed counterpart to the ROSAT sources). All are numbered 476, 499, 512 and 647 in Figure 1 (object no: determined to be in, or close to, the ASCA error circle. These location in the field identified. Only four such objects were third of the colour-magnitude plot were examined and their likely to be a HXRB and the modulation signature atypical of that seen from such objects.

Consequently, it was felt necessary to revisit the linking of this optical object with the ASCA pulsar to make sure that some other candidate was not more appropriate within the X-ray error circle.

3 OPTICAL & IR COUNTERPART SEARCH

Optical photometric observations were taken from the SAAO 1.0m telescope on 2 October 1996. The data were collected using the Tek8 CCD giving a field of $\sim 6 \times 6$ arcminutes and a pixel scale of 0.6 arcsec/pixel. Observations were made through standard Johnson V & R filters plus an H$\alpha$ filter. The standard star E950 was used for photometric calibration. From these CCD frames a R-H$\alpha$ index was created and this was plotted against the V band flux for $\sim 800$ objects.

On the assumption that our optical counterpart was likely to be a H$\alpha$ bright system, all the objects in the top third of the colour-magnitude plot were examined and their location in the field identified. Only four such objects were determined to be in, or close to, the ASCA error circle. These are numbered 476, 499, 512 and 647 in Figure 1 (object no: 512 is the proposed counterpart to the ROSAT sources). All the other objects with an R-H$\alpha$ index $\geq -1.0$ lie well away from the region of interest.

The average $B$, $V$ &$I$ colours of these four objects were extracted from the OGLE database and are presented in Table 1. In addition, IR magnitudes for two of the objects are also presented that were extracted from the 2MASS survey data base, the other 2 candidates were too faint to be detected in that survey.

To confirm the nature of Object 512 as a B or Be star, optical spectra were obtained on 3 occasions (1 Nov 1999, 15 Sep 2000 and 22 Oct 2000) from the ESO 1.52-m telescope at La Silla Observatory, Chile, equipped with the Boller & Chivens spectrograph. The no: 33 holographic grating was used, which gives a resolution of $\sim 1A$/pixel. Since no obvious variations were seen between the spectra they were combined to increase the signal-to-noise ratio. The resulting spectrum is presented in Figure 2. In this figure our spectrum is compared to that of the B0.5V standard 40 Per. Object 512 is obviously a Be star, with H$\beta$ and H$\gamma$ in emission and most other lines affected by emission components. The presence of weak H$\eta$ $\lambda 4686$ Å places the object close to B0V (Walborn & Fitzpatrick 1990). Though several O$\eta$ lines are present, C$\chi$ $\lambda 4650$ Å is surprisingly absent. The relatively weak Si$\chi$ and Si$\kappa$ lines seen in 40 Per are not easily detectable in object 512, which is compatible with the lower metallicity of the SMC, but unexpected in view of the rather strong O$\eta$ lines.

4 OGLE AND MACHO DATA

The field of AX J0051-733 lies within the areas covered by both the OGLE and MACHO monitoring programmes. Hence excellent photometric coverage exists for the brighter counterparts for a total of nearly 7 years.

Detailed I band photometry was obtained from the OGLE data base for objects numbered 499 (no significant variability), 647 (some evidence for long term changes comparable to the length of the data set) and 512. As Cook (1998) and Coe & Orosz (2000) have already shown from subsets of the OGLE/MACHO data, this object exhibits a strong clear sinusoidal modulation at $\sim 0.7d$. The combined OGLE and MACHO data set for this object is presented in Figure 3.

Though the precise modulation is not obvious from this figure, it clearly shows the varying amplitude of the modulation over the data set. If the total data set is analysed for periodic behaviour, then a period of 0.70872d is determined using a Lomb-Scargle analysis. However, this period is the average of the data, because if one splits up the data set into 150d samples a slightly different period is found for each one.

Table 1. Optical photometric values taken from the OGLE database and IR values from the 2MASS survey.

| ID   | V  | B-V | V-I | J  | K  |
|------|----|-----|-----|----|----|
| 476  | 18.70 | 1.00 | 1.08 | -  | -  |
| 499  | 17.21 | -0.08 | 0.15 | -  | -  |
| 512  | 15.44 | -0.03 | 0.17 | 15.3 | 14.8 |
| 647  | 15.69 | 0.07 | 0.26 | 16.5 | 15.9 |

* http://sirius.astrouw.edu.pl/ogle
† http://wwwmacho.mcmaster.ca
Figure 2. Blue spectrum of Object 512 (upper spectrum) compared to a B0.5V standard at a similar resolution. Note the presence of relatively strong Na $\text{II} \lambda 3934\text{Å}$ in the spectrum of Object 512, presumably of interstellar origin.

Figure 3. Approximately 7 years of photometric observations of the proposed counterpart to AX J0051-733 taken from the MACHO and OGLE data bases. The date axis has MJD = JD - 2450000. In both cases the magnitude scale is indicated, though the MACHO one is described as "approximately R".

Figure 4 illustrates the Lomb-Scargle power spectrum for one such subset of data. To check on the aliasing with the Nyquist frequency and the effects of the window function, a simulated data set was created. This data set consists of a single sine wave with period and amplitude determined from the original data sampled with exactly the same temporal structure as the original data. As can be seen by comparison between the two power spectra in Figure 4, there is no significant difference. Thus the conclusion is that there are no other frequencies present in the original data set.

The shape of the modulation was determined by folding one of the MACHO and OGLE data sets at the determined period for that data set. The result of this is illustrated in Figure 5. Lightcurves from four different filters are shown in this figure. In the case of the V band, the OGLE data are rather sparse since this is not their main filter, and so the

Figure 4. Comparison of a Lomb-Scargle power spectrum for a ~150d section of MACHO data (lower panel) and a simulated data set (upper panel). The simulated data set consists of a pure sine wave with the same window function as the raw data (see text for more details).
Figure 5. The lightcurves obtained by folding a \(\sim 150\)d sample of MACHO and OGLE data at the period of 1.4174d. Because the OGLE \(V\) filter coverage is very sparse, data from several observations at SAAO in this band have been added to the illustrated data set. The magnitude scale on the left only refers to the OGLE \(I\) band data, all the other photometric bands have been arbitrarily shifted upwards by a constant amount to fit conveniently on the figure. In each case the data sets have been phase shifted to coalign with the OGLE \(I\) band data set (see text for further details). The uppermost curve shows the colour information obtained from the same MACHO data set used to construct the light curve in the figure.

Figure 6. The lower curve shows the period history determined from the combined MACHO and OGLE data sets. If the source is binary system then we should expect the true binary period to be twice the value indicated on the left hand axis. The upper curve shows the amplitude of a sine wave fitted to each data block. In both cases a typical error bar is indicated. The time axis has MJD = JD - 2449000.

5 DISCUSSION

5.1 Optical candidate

In trying to establish the optical counterpart to the ASCA pulsar one must keep in mind that the ROSAT source is too weak to have shown any detectable pulsations. Thus putting the ROSAT source aside for the moment, the most objective approach is to just look at the colour-magnitude diagram (Figure ??). This diagram reveals just two objects inside the best ASCA positional error circle - nos. 512 and 499. The other two objects lie in, or very close to the original ASCA circle, but are now significantly less attractive as counterparts. Object 499 is very faint compared to all other known counterparts to HMXBs in the SMC, which typically have \(V \sim 15 - 16\). Its colours and the presence of \(H\alpha\) in emission suggest a B3-4Ve star - a somewhat later spectral type than most other Be/X-ray binary systems. Its OGLE lightcurve reveals nothing of interest and it is not a detectable IR source in the 2MASS data. Hence it cannot be a strong contender for the counterpart to AX J0051–733.

On the other hand, Object 512 has \(V = 15.4\) and a significant IR flux at \(J = 15.3\). Both of these make it look like a classic counterpart to a Be/X-ray binary system. If we compare this object to another SMC X-ray pulsar system,
1WGA J0053.8–7226 (Buckley et al, 2001), we find it is extremely similar. In 1WGA J0053.8–7226 we have \((B - V) = -0.06\) compared to \(-0.03\) in Object 512, and \((J - K) = 0.62\) compared to 0.51 in Object 512. The \(E(B - V)\) value found for many other SMC counterparts to Be/X-ray systems is \(\sim 0.25\) (a combination of extinction to the SMC plus local extinction due to circumstellar material). Applying this to the observed values for Object 512 given in Table 1 leads to an identification for the spectral type of B0III-V. Thus even before one considers the \(V\) leads to an identification for the spectral type of B0III-V. Thus even before one considers the local extinction due to circumstellar material). Applying this to the observed values for Object 512 given in Table 1 leads to an identification for the spectral type of B0III-V. Thus even before one considers the \(ROSAT\) source, one is led inexorably to Object 512 being the prime candidate for the optical counterpart to AX J0051-733. The presence of a convincing \(ROSAT\) source at the same position adds significant extra weight to this conclusion.

The optical spectrum of Object 512 presented in Figure 2 is no later and perhaps slightly earlier than the comparison standard. From the colours presented in Table 1 and assuming \((B - V)_0 = -0.26\) (Wegner 1994), this results in an extinction value of \(E(B - V) = 0.23\), which confirms the number used above in interpreting just the photometry. Assuming standard reddening, \(A_V = 0.71\) and therefore, assuming a distance modulus to the SMC \((M - m) = 18.9\), the absolute magnitude for Object 512 is \(M_V = -4.2\), which is in rather good agreement with a spectral type in the B0-B0.5V range.

### 5.2 Optical modulation

The strong sinusoidal optical modulation of Object 512 is challenging to interpret in terms of a traditional Be/X-ray binary model. Firstly, the expected binary period of AX J0051–733 based on the Corbet diagram (Corbet, 1986) is 100-200d. Secondly, a binary period of just 1.4d involving a Be star implies an extremely tight orbit – the Keplerian orbital radius would be \(\sim 14\) solar radii and the B0 star has a size of \(\sim 8\) solar radii. Thirdly, if the period is really decreasing at a rate of 13.5 s/year then this implies (Huang 1963) a mass transfer of \(10^{-5}M_\odot/\text{year}\) for mass transfer between an \(18M_\odot\) Be star and a \(1.4M_\odot\) neutron star – which is not only much larger than that typically observed in HMXB systems \((\lesssim 10^{-8}M_\odot/\text{year in most cases})\), but would also imply a much higher X-ray luminosity unless the accretion mechanism is extremely inefficient at converting gravitational potential into X-rays.

Mass transfer rates of this magnitude are deduced to exist in the EB binary system \(\beta\) Lyrae which is changing its \(\sim 13\)d orbital period at a rate of 19s/year (van Hamme, Wilson & Guinan 1995). In this case the change is to a longer period with the mass transferring from the smaller B6-8 star to the more massive Be star. In our case, the mass would be flowing in the opposite direction, i.e. from the more massive object to a less massive one. The optical lightcurve of \(\beta\) Lyrae is similar to the one presented here for Object 512, but with the notable difference that in \(\beta\) Lyrae the two minima are not of the same depth.

In fact the symmetry of the light curve is much more suggestive of a W UMa type system. Unfortunately, the observed period of 1.4d is much greater than any such reported system in the SMC (Rucinski 1997). The maximum observed period is 0.8d and our period is well off the end of the distribution. In addition, it is perhaps worth noting that the predicted \((V - I)\) colour obtained from the distribution of such objects and our binary period of 1.4d is \(+0.026\), but from Table 1 it can be seen that the observed \((V - I)\) for Object 512 is 0.17. Even allowing for interstellar extinction this further adds to it being unlikely that this system is of this class.

The possibility of a blended variable star plus Be star can be considered. For example, a chance superposition of Be star (to give the observed colours) plus Cepheid or RR Lyrae (to give the optical modulation). However, all of these models can be ruled out because of either the magnitude of the period, or the depth of modulation, or the shape of the lightcurve.

Interestingly the optical modulation is somewhat similar to the short periodic modulation seen by Balona (1992) in Be stars in the cluster NGC330 in the SMC. In this case Balona attributes this modulation to surface features on the rapidly rotating objects. However, how the period of such objects could change on a timescale of years is not clear, unless the star is in a very wide binary system. It is possible that the data in Figure 6 could be fitted to \(\sim 10\) year sinusoidal modulation, but then the orbit of the neutron star would be so distant from the Be star that it hard to see how accretion could ever occur. In addition X-ray outbursts have been detected 3 times over 2 years from this system (Laycock, private communication) making such a long orbit unlikely. Perhaps further optical data may clarify exactly what the shape of the period change is on such timescales.

### 5.3 A triple system?

We are left with no convincing traditional scenario to explain all the observational data. It is very hard to see how the orbital period change seen in Figure 6 could possibly be caused by mass loss from a normal B0 star at a rate of \(10^{-5}M_\odot/\text{year}\). One other possibility perhaps worth considering is that AX J0051–733 is a triple system – Be star plus another star in a tight 1.4d orbit, and the neutron star in a highly eccentric 100–200d orbit around the pair. Such a system could not only be intrinsically very stable since most of the mass is concentrated in the inner binary pair, but the transfer of angular momentum from the inner binary to the orbit of the neutron star might also explain the evolution of the orbital period.

Eggleton & Kiseleva (1995) derive a critical parameter \(X_{\text{crit}}\) for a stable triple system, which is the period ratio between the outer and inner orbits. For a system to be stable it is required that the ratio of the orbital periods be greater than \(X_{\text{crit}}\). If we assume that our inner 1.4d binary consists of a \(B0V\) star \((M=18M_\odot)\) and a \(1M_\odot\) star, while the third outer body is a \(1.4M_\odot\) neutron star, then this parameter \(X_{\text{crit}} = 17\). Assuming that the outer orbital period is actually given by the position of AX J0051–733 on the Corbet diagram and has a value of \(\sim 100\)d, then this criterion is easily satisfied.

Bailyn & Grindlay (1987) provide a formula for the rate of change of size of the major axis of such a tight binary (their Equation 7). Using their relationship, and assuming one of the binary partners is the observed B0 star, then it is possible to predict the rate of change of orbital period as a function of the mass of the other star in the inner binary. For masses of the order 15-20\(M_\odot\) the predicted period change is \(\sim 10\) s/year. This number is in good agreement.
with the observed value of 13s/year and suggests that the inner binary may, in fact, consist of two very similar B-type stars. This, of course, would not present any problems to the observed photometric or spectroscopic parameters of the system. Even assuming that the two stars contribute equally to the luminosity of the system would mean that their intrinsic magnitudes are \( M_V = -3.5 \), still compatible with B0.5Ve. Furthermore, the Eggleton & Kiseleva criterion remains comfortably satisfied for such a system. The main problem raised by such scenario though would be the very little space left between the two stars for a Be disk.

However, the evolution of this system would have to have been very different from a classic Be/X-ray binary system. In particular, the neutron star progenitor has probably evolved without any mass-transfer to either of the objects in the inner binary. Consequently it must have been much more massive in order to have reached its current state so long ahead of the other stars in the system. Clearly this solution for AX J0051−733 is also not without challenges.

6 CONCLUSIONS

Detailed optical observations and analysis have been carried out of the proposed counterpart to AX J0051-733. The most likely counterpart has been identified on the basis of its colours and \( H\alpha \) emission. However this object is revealed to have a strong 0.7/1.4d modulation from long-term MACHO and OGLE observations. Furthermore this strong period is shown to be changing at a rate of 13.5s/year. It is hard to reconcile all these observations with the classic Be/X-ray binary model and further studies of this system are urgently required.

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