OGLE observations of four X-ray binary pulsars in the SMC

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ABSTRACT

This paper presents analysis and interpretation of OGLE photometric data of four X-ray binary pulsar systems in the Small Magellanic Cloud: 1WGA J0054.9-7226, RX J0050.7-7316, RX J0049.1-7250, and 1SAX J0103.2-7209. In each case, the probable optical counterpart is identified on the basis of its optical colours. In the case of RX J0050.7-7316 the regular modulation of its optical light curve appears to reveal an ellipsoidal modulation with a period of 1.416 days. Using reasonable masses for the neutron star and the B star, we show that the amplitude and relative depths of the minima of the I-band light curve of RX J0050.7-7316 can be matched with an ellipsoidal model where the B star nearly fills its Roche lobe. For mass ratios in the range of 0.12 to 0.20, the corresponding best-fitting inclinations are about 55 degrees or larger. The neutron star would be eclipsed by the B star at inclinations larger than \( \approx 60^\circ \) for this particular mass ratio range. Thus RX J0050.7-7316 is a good candidate system for further study. In particular, we would need additional photometry in several colours, and most importantly, radial velocity data for the B star before we could draw more quantitative conclusions about the component masses.

Key words: stars: emission-line, Be, binaries.

1 INTRODUCTION

The Magellanic Clouds present a unique opportunity to study stellar populations in galaxies other than our own. Their structure and chemical composition differs from that of the Galaxy, yet they are close enough to allow study with modest sized ground based telescopes. The study of any stellar population in an external galaxy is of great interest because any differences with the same population in our own Galaxy will have implications on the evolutionary differences of the stars within the galaxies.

Be/X-ray binaries and supergiant X-ray binaries represent a subclass of High Mass X-ray Binaries (HMXRB’s). In these Be/X-ray binaries the primary is an early type emission line star, typically 10 to 20 solar masses, and the secondary is a neutron star.

The Be stars are early type luminosity class III-V stars which display Balmer emission (by definition) and a significant excess flux at long (IR - radio) wavelengths (dubbed as the infrared excess). These have been successfully modelled as recombination emission (Balmer) and free-free free-bound emission (infrared excess) from a cool dense wind. However, observations in the ultraviolet regime indicate a highly ionised, far less dense wind. These apparent inconsistencies are explained in current models by assuming a non-spherically symmetric wind structure, with a hot, low density wind emerging from the poles of the star, and a cool, dense wind from the equatorial regions (the circumstellar disk).

The X-ray emission is caused by accretion of circumstellar material onto the compact companion. As a consequence, many of the Be/X-ray binaries are known only as transient X-ray sources, with emission occurring when accretion is enhanced during periastron passage or when the envelope expands and reaches the neutron star. Quiescent level emission, though low, has been detected from some of these systems.

Observations of the HMXB’s in the Magellanic Clouds appear to show marked differences in the populations. The X-ray luminosity distribution of the Magellanic Clouds sources appears to be shifted to higher luminosities relative to the Galactic population. There also seems to be a higher incidence of sources suspected to contain black holes (Clark et al. 1978; Pakull 1989; Schmidtke et al. 1994). Clark et al. (1978) attribute the higher luminosities to the lower metal abundance of the Magellanic Clouds, whilst Pakull (1989)
Figure 1 shows the distribution of the 11 known X-ray pulsars superimposed on an outline image of the Small Magellanic Cloud. The OGLE scan regions are described in Udalski et al. (1998) from which it can be seen that 7 out of the 11 pulsars lie outside the region covered by that experiment. In fact the overall distribution of these X-ray pulsars is far from consistent with the general visible mass distribution of the SMC - a fact undoubtedly related to the details of star formation in this object.

In general the OGLE data cover the period June 1997 to February 1998 and primarily consist of I band observations, though some observations were also taken in B and V. Most of the work presented in this paper consists of identifying the possible optical counterparts to X-ray pulsars within the OGLE database, determining their colours and searching for regular time variability indicative of a binary period.

2.1 1WGA J0054.9-7226

This source was catalogued using ROSAT by Kahabka and Pietsch (1996) and identified as an X-ray pulsar with a period of 59s by RXTE (Marshall & Lochner 1998). An optical study of the X-ray error boxes clearly identified one particular object with strong Hα emission as the counterpart to the X-ray source (Stevens, Coe & Buckley 1998). This object was identified within the OGLE database as object number 70829 in Field 7 with the following magnitudes : V=15.28, B=15.24 and I=15.13 (all magnitudes have errors of ± 0.01). Its position, accurate to 0.1 arcsec, is RA=00 54 56.17, dec=−72 26 47.6 (2000).

Its position on a colour-colour diagram is shown in Figure 2 along with the nearest 70-80 other stars. The position of the candidate is consistent with that expected for a B0-B1 object. More precisely, taking V=15.28 and using the distance modulus to the SMC of (m-M)=18.9, together with a reddening of E(B-V) in the range -3.8 to -4.5. A B0V has an absolute V magnitude of -4.0 and a B1III star has V=-4.4. In addition, it is worth noting that the observed (B-V)= -0.04 is almost the same as that found for another SMC X-ray counterpart RX J0117.6-7330 (Coe et al. 1998) which was identified with a star in the range B1-B2 (luminosity class III-V). Thus one can be fairly confident in a similar spectral class for 1WGA J0054.9-7226.

Figure 3 shows the power spectrum of the source obtained using CLEAN on the 96 daily I band observation points. A strong peak occurs at a period of 14.26d. However, when the data are folded at either that period or twice the period, no strong light curve emerges. There is some evidence of a small sinusoidal modulation with a semi-amplitude of 0.008±0.001 magnitudes which presumably is the source of the peak in the power spectrum seen in Figure 3.

2.2 RX J0050.7-7316

This 323s X-ray pulsar was initially catalogued by ROSAT and subsequently discovered to be a pulsar by Yokogawa & Koyama (1998) using the ASCA satellite. Subsequently Cook (1998) identified one of the objects in the 1 armin X-ray error circle as having a period of 0.708d using data from...
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Figure 2. Colour-colour plots for objects in the immediate vicinity of 1WGA J0054.9-7226. The proposed counterpart is indicated by a star symbol.

In the OGLE database this source was identified as Object number 180026 in Scan Field 5. Its position is given as RA = 00 50 44.7, dec = -73 16 05 (2000) with uncertainties of ±0.1 arcsec. Its colours are V=15.44, B=15.41 and I=15.27 with uncertainties of ±0.01 magnitudes. A colour-colour plot of objects in the immediate vicinity of the source is shown in Figure 4, from which the blue nature of the counterpart is very clear.

A CLEAN periodicity search of the 134 I band data points clearly revealed a periodicity in the data of 0.708d - see Figure 5. This is exactly the same as reported by Cook (1998). A full discussion of the light curve of this source is presented in Section 3 below.

2.3 RX J0049.1-7250

This X-ray source was identified as an X-ray pulsar with a period of 75s by RXTE (Corbet et al. 1998) after its discovery by Kahabka and Pietsch (1996) from ROSAT data. Stevens, Coe & Buckley (1998) carried out a photometric study of the objects in the X-ray error box and concluded that Star 1 (a previously known Be star) was the most likely counterpart. However, a second Be star (denoted Star 2 in their paper) lies just on the edge of the ROSAT X-ray positional uncertainty and cannot be ruled out.

Both of these objects were identified in the OGLE data base in Scan Field 5. The data on these two objects are presented in Table 1.

A colour-colour plot for the whole of the region surrounding these two sources is shown in Figure 6. From this figure it can be seen that the two candidates both lie at the blue edge of the distribution, consistent with their Be star nature. Apart from this there appears to be nothing else remarkable about their colours.

Both of their I band lightcurves were searched using the CLEAN algorithm for possible periodicities similar to those

Table 1. OGLE data on the two candidates for RX J0049.1-7250. Errors on position are ±0.1 arcsec and on magnitudes are ±0.01.

| Star 1 | Star 2 |
|--------|--------|
| RA (2000) | 00 49 03.3 | 00 49 06.2 |
| dec (2000) | -72 50 52.0 | -72 51 14.4 |
| V | 16.92 | 17.25 |
| B | 17.01 | 17.06 |
| I | 16.68 | 17.18 |
| Ogle ID | 65517 | 60831 |
| No. I band observations | 146 | 147 |
found in the previous two systems, but nothing was seen in the period range 1-50d. A modulation upper limit of ≤ ±0.01 magnitudes may be set based upon the signals seen from similar data runs of other sources in this work.

2.4 1SAX J0103.2-7209

This object was identified in 1998 by the SAX satellite (Israel & Stella 1998). Its X-ray signal is modulated at a period of 345s and it has been identified with the brightest object in the X-ray error circle, a V=14.8 magnitude Be star. This star has previously been proposed as the counterpart to an earlier X-ray source RX J0103-722 by Hughes & Smith (1994). The proposed optical counterpart - a bright Be star - was identified in the OGLE data base as Object number 173121 in Scan Field 9. Its magnitudes are given as V=14.8, B-V=-0.089 and V-I=0.132 (all magnitudes have errors of ±0.01). Its position is given as RA=01 03 13.9, declination = -72 09 14.0 (2000), with a positional uncertainty of ±0.1arcsec.

A colour-colour plot of objects in the region around the source is shown in Figure 7. The position of the proposed candidate is marked, and it is obviously in a very similar location on this diagram to the other sources discussed in this paper - confirming the Be star nature of this object. There are many more objects of similar magnitude within the SAX X-ray uncertainty circle (40 arcsec), but Hughes & Smith (1994) obtained a much smaller X-ray error circle (~10 arcsec) using ROSAT which includes this Be star. It is therefore very likely that this is the correct counterpart to the X-ray pulsar.

Timing analysis of 104 daily I band photometric measurements from OGLE revealed no evidence for any coherent period in the range 1 to 50 days with a modulation upper limit of ≤ ±0.02 magnitudes.

3 MODELLING THE LIGHT CURVE OF RX J0050.7-731

Using (m-M)=18.9 and E(B-V)=0.06 to 0.28, we find an absolute V magnitude of -3.65 to -4.33 for the mass donor star of RX J0050.7-731. This corresponds to a spectral type of B1, luminosity class III-V. According to Gray (1992), a B0V star has a mass of 13.2 $M_\odot$ and a radius of 6.64 $R_\odot$, and a B2V star has a mass of 8.7 $M_\odot$ and a radius of 4.33 $R_\odot$. In order to get some idea of the scale of this binary, we can use Eggleton’s (1983) formula to compute the relative radii of the Roche lobes

$$\frac{R_{L1}}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})},$$

(1)

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Figure 6. A colour-colour plot of the objects in the immediate vicinity of the X-ray source RX J0049.1-7250. The proposed counterparts are indicated by star symbols. Star 2 lies to the left of Star 1 in this figure.

\[ a = 4.2P_{\text{day}}^{2/3}(M_{\text{total}}/M_\odot)^{1/3} R_\odot, \]

(2)

(where \( q \) is the mass ratio), and Kepler’s Third Law to compute the separation between the two components (assuming a circular orbit)

\[ \alpha = 4.2P_{\text{day}}^{2/3}(M_{\text{total}}/M_\odot)^{1/3} R_\odot, \]

(2)

(where \( P_{\text{day}} \) is the orbital period in days). We find \( R_{L1} = 3.89 R_\odot \) using \( P_{\text{day}} = 0.708 \), \( M_X = 1.4 M_\odot \), and \( M_B = 8.7 M_\odot \). In this case where we assumed the 0.708 day periodicity was the orbital period, the B star clearly would overfill its Roche lobe by a large margin. If we assume the orbital period is 1.416 days, then we find \( R_{L1} = 6.17 R_\odot \) using \( M_X = 1.4 M_\odot \), and \( M_B = 8.7 M_\odot \). We conclude the orbital period of RX J0050.7-7316 must be 1.416 days in order for the B star to fit within the Roche lobe. Even then, the B star still fills a large fraction of its Roche lobe.

Folding the I and V band data for RX J0050.7-7316 at a period of 1.416 days produces the light curves shown in Figure 8. Note that the gaps exist in the V band data because there were much fewer observations carried out in this band (32 compared to 134 I band measurements). The light curves are double-wave with two maxima and two minima per cycle. Since the B star probably comes close to filling its Roche lobe and is hence tidally distorted, we may presume that the cause of the optical modulation is the well-known ellipsoidal variations (e.g. Avni & Bahcall 1975; Avni 1978). The amplitude of the ellipsoidal light curve depends on three basic parameters: the inclination of the orbital plane, the mass ratio, and the Roche lobe filling fraction of the distorted star. Thus one can in principle model ellipsoidal light curves and obtain constraints on the system geometry. However, the observed light curve can be altered by the addition of extra sources of light and by eclipses. The amount of extra light can depend on the orbital phase, as in light due to X-ray heating of the secondary star, or can be independent of phase, such as light from an uneclipsed “steady” accretion disk. One must account for these extra sources of light if one is to obtain reliable constraints from ellipsoidal modelling.

We will focus here on only the I light curve of RX J0050.7-7316, since the V light curve of this object is much less complete. We used the modified version of the Avni (1978) code described in Orosz & Bailyn (1997) to model the light curve. This code uses Roche geometry to describe the shape of the secondary star and accounts for light from a flat, circular accretion disc and for extra light due to X-ray heating. The parameters for the model are the parameters which determine the geometry of the system: the mass ratio \( Q = M_X/M_B \), the orbital inclination \( i \), the Roche lobe filling factor \( f \), and the rotational velocity of the secondary star; the parameters which determine the light from the secondary star: its polar temperature \( T_{\text{pole}} \), the linearized limb darkening coefficients \( u(\lambda) \), and the gravity darkening expo-
eclipse the B star, we will keep the radius of the disk \(r_d\) as a free parameter. Small changes in the disk radius can lead to relatively large changes in the eclipse profile, whereas the eclipse profile is much less sensitive to changes in the disk opening angle \(\beta_{\text{rim}}\). Finally, we will assume the B star is tidally locked so that its rotational period is the same as the orbital period. In this case the system geometry is specified by the mass ratio, inclination, and the Roche lobe filling factor of the B star. Hence we have four free parameters in the model: \(i, Q, f,\) and \(r_d\).

We do not know the absolute orbital phase of RX J0050.7-7316, so we simply adjusted the phase so that the deeper minimum is at phase 0.5. We computed a grid of models in the inclination-mass ratio plane, where the inclinations range from 40 to 70 degrees and the mass ratios ranged from 0.05 to 0.35. At each point in the plane, the values of \(i\) and \(Q\) were fixed at the values corresponding to the point in the grid and the values of \(f\) and \(r_d\) were adjusted to minimize the \(\chi^2\) of the fit, where we fit only the points near the two maxima and two minima. Figure 9 shows the contour plot of \(\chi^2\) values. Formally, the best-fitting model has a mass ratio of 0.34 and an inclination of 50°. However, the mass of the B star probably is in the range of \(\approx 7 - 12 \, M_\odot\) (Gray 1992), and the mass of the neutron star probably is not too different from \(1.4 \, M_\odot\). Hence the mass ratio is likely to be in the range of 0.12 to 0.20. If we restrict our attention to fits with mass ratios less than 0.2, we see that the corresponding best-fitting values of the inclination are 55° or higher. We also show the inclination at which the neutron star would be eclipsed by the B star (thick solid line). The model fits to the I light curve indicate that RX J0050.7-7316 has a fairly high inclination and might show X-ray eclipses. It turns out that the optical light curve is altered very little by the grazing eclipse of the star by the rim of the disk, and of the nearly total eclipse of the disk by the star. Figure 10 shows a representative model light curve with \(i = 60°\), \(Q = 0.20, f = 0.99,\) and \(r_d = 0.33\). The amplitude of the observed I light curve is matched reasonably well, and the relative depths of the two minima are also matched reasonably well. However, there are relatively large deviations from the model, especially between phases 0.4 and 0.6.

It is difficult to draw quantitative conclusions from the modelling, given the fact that we do not yet have dynamical data. We have shown that if we take the I light curve at face value, the inclination probably is large enough to be an X-ray eclipsing system if we assume reasonable values of the mass ratio. There may be systematic errors in our analysis. For example, we assumed the OGLE light curve represents the true ellipsoidal component from the secondary star. Cook et al. (1998) report a long-term trend in the baseline brightness in data from the MACHO collaboration. Such a trend could alter the amplitude of the folded light curve. It would be worthwhile to obtain more complete photometry of this source over the course of a several night run, rather than a few observations per night over an entire season as in the OGLE and MACHO observations. The light curves obtained over a short run would be much less prone to errors introduced by the long-term baseline brightness changes. Furthermore, better sampling near the minima is useful if there are grazing eclipses since there are subtle changes in the shape of the light curve near the minima caused by eclipses. Finally, it would be useful to have a radial velocity curve of the

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**Figure 8.** The OGLE I band data for RX J0050.7-7316 folded at the proposed binary period of 1.416d. The upper data are the folded I band points and the lower data are from the V band observations.

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\begin{align*}
\text{The limb darkening coefficients were taken from Wade} & \text{ and Rucinski (1985). We can neglect the extra light due to X-ray heating since the optical luminosity of most HMXBs is dominated by the mass donor star (van Paradijs & McClintock 1995). We carried out some numerical experiments and found that the light curve shapes did not depend on the values of } L_x, W, \text{ and } a. \text{ For definiteness we used } L_x = 2 \times 10^{36} \text{ erg s}^{-1}, W=0.5, \text{ and } a = 11 R_\odot. \text{ In that same vein, we found that the optical flux from the accretion disk was only a small fraction (} \lesssim 0.5\% \text{) of the optical flux from the B star for a wide range of reasonable values of } r_d, \beta_{\text{rim}}, T_d, \text{ and } \xi. \text{ Again for definiteness we adopt } \beta_{\text{rim}} = 4^\circ, T_d = 6000 \text{ K, and } \xi = -0.75 (\text{the value expected for a steady-state accretion disk, Pringle 1981). Since the accretion disk may partially}
\end{align*}
\]
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Figure 9. A contour plot of the $\chi^2$ values for model fitting to the folded I light curve of RX J0050.7-7316. Eleven points near the two maxima and two minima were included in the fitting region. The filled circle at $i = 52^\circ$ and $Q = 0.34$ marks the location of the lowest $\chi^2$ value ($\chi^2_{\text{min}} = 24.55$). The dashed lines indicate the likely range of mass ratios: $0.12 \leq Q \leq 0.2$, which corresponds to $M_{\text{NS}} \approx 1.4 M_\odot$ and $7 \leq M_B \leq 12 M_\odot$. The neutron star is eclipsed by the B star in models with inclinations and mass ratios that are to the right of the thick line.

Figure 10. Comparison of a representative ellipsoidal model ($i = 60^\circ$, $Q = 0.20$, $f = 0.99$, and $r_d = 0.33$) and the folded I-band data for RX J0050.7-7316. The amplitude and relative depths of the minima are roughly matched by the model. However, there are relatively large deviations from the model, especially between phases 0.4 and 0.6.

B star and a complete X-ray light curve so that dynamical mass estimates can be derived.

4 CONCLUSIONS

This paper presents analysis and interpretation of OGLE photometric data of the SMC X-ray pulsars 1WGA J0054.9-7226, RX J0050.7-7316, RX J0049.1-7250, and 1SAX J0103.2-7209. In each case, the probable optical counterpart is identified on the basis of its colours. In the case of RX J0050.7-7316, the regular modulation of its optical light appears to reveal binary motion with a period of 1.416 days. We show that the amplitude and relative depths of the minima of the I-band light curve of RX J0050.7-7316 can be matched with an ellipsoidal model where the B star nearly fills its Roche lobe. For mass ratios in the range of 0.12 to 0.20, the corresponding inclinations are about 55 degrees or larger. Thus the neutron star may be eclipsed by the B star in this system. Although the present ellipsoidal model is not perfect, additional observations of RX J0050.7-7316 should be obtained. In particular, additional photometry in several colours, and most importantly, radial velocity data for the B star will be needed before we can draw more quantitative conclusions about the component masses.

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