Optical studies of two LMC X-ray transients: RX J0544.1–7100 and RX J0520.5-6932 *

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ABSTRACT

We report observations which confirm the identities of the optical counterpart to the transient sources RX J0544.1-7100 and RX J0520.5-6932. The counterparts are suggested to be a B-type stars. Optical data from the observations carried out at ESO and SAAO, together with results from the OGLE data base, are presented. In addition, X-ray data from the RXTE all-sky monitor are investigated for long term periodicities. A strong suggestion for a binary period of 24.4d is seen in RX J0520.5-6932 from the OGLE data.

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

1 INTRODUCTION

The Be/X-ray and supergiant binary systems comprise the class of massive X-ray binaries. 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.

1.1 RX J0544.1–7100

The source 1SAX J0544.1–710 was detected by BeppoSAX in October 1996 (Cassumano et al, 1998) at a flux corresponding to a luminosity of 9 × 10³⁵ erg/s. Their observations revealed an X-ray pulse period of 96s. The transient, variable nature of the source was reported by Haberl et al (1998) when they linked the BeppoSAX source with a ROSAT source, RX J0544.1–7100 (Haberl & Pietsch 1999). Haberl et al also reported a possible optical counterpart lying within the 8 arcsec ROSAT error circle. Subsequently, Haberl & Pietsch (1999) reported more details of the ROSAT source and refined the error circle to just 3.3 arcsec radius which includes one obvious optical counterpart. The PSPC spectrum indicated that it was the hardest source in their sample of 27 LMC objects they studied. The totality of the X-ray behaviour strongly suggests that the object is a member of the Be/X-ray binary class.

Reported here are optical, infra-red and X-ray measurements of the system. The data confirm the proposed identity of the counterpart to RX J0544.1–7100, and the counterpart is shown to be most consistent with a main sequence B0V star.

1.2 RX J0520.5-6932

The source RX J0520.5-6932 was discovered by ROSAT (Schmidtke et al, 1994) at a luminosity of 5 × 10³⁴ erg/s and identified with a V~14 magnitude star. Optical spectral observations carried out by Schmidtke et al indicated a O8e type star with radial velocity measurements consistent with LMC membership. Since the source was not detected by Einstein it is probably exhibiting X-ray variability consistent with it being a member of the Be/X-ray binary group of sources - though its spectral classification is unusually early (Negueruela 1998). Further optical observations

* Partially based on observations collected at the South African Astronomical Observatory and the European Southern Observatory, Chile (ESO N64.H-0059)
by Schmidtke et al (1996) revealed evidence for small photometric changes up to a few tenths of a magnitude.

2 OGLE DATA

The Optical Gravitational Lensing Experiment (OGLE) is a long term observational program with the main goal of searching for dark, unseen matter using the microlensing phenomenon (Udalski et al. 1992).

In general the OGLE data cover the period June 1997 to February 2000 and primarily consist of I band observations, though some observations were also taken in the V band. The optical counterparts were identified in the OGLE data base and all the photometric measurements extracted. Figure 1 (top panel) shows the optical lightcurve for RX J0544.1-7100 obtained from the OGLE I band data.

The OGLE data of RX J0520.5-6932 are shown in Figure 2.

Figure 3 shows the power spectrum of RX J0544.1-7100 obtained using the Lomb-Scargle technique on 219 I band data points obtained over the period 5 Oct 1997 - 27 March 2000. Periods in the range 10 - 500 days were investigated. The largest peak shown in Figure 3 corresponds to a period of 286d and undoubtably arises from the variability on several long timescales evident in Figure 1.

Figure 4 shows the Lomb-Scargle power spectrum obtained for RX J0520.5-6932 using the same search parameters as those used for RX J0544.1-7100. In this case there is a very clear and strong peak corresponding to a period of 24.45d. The lower panel in Figure 2 shows the average folded lightcurve compared to the first, and most comprehensive, set of OGLE data. Phase zero has been set to JD2450008.6 corresponding to the peak of the optical flux.

3 ROSSI X-RAY TIMING EXPLORER ALL-SKY MONITOR DATA

Data from the RXTE all sky monitor experiment were obtained from the public archive for RX J0544.1–7100. Since the signal from this object is very weak, the data shown in the lower panel of Figure 1 have been averaged over 1 week intervals.
Looking carefully at the X-ray lightcurve in Figure 1 it is clear that a significant X-ray signal is only present in the first half of the data run. Therefore only X-ray data covering the epoch TJD 100-1000 were searched for periodic signals. The raw daily data for this period were then analysed using the same Lomb-Scargle algorithmic technique as the optical data. No periodic behaviour was identified in these X-ray data.

The peak ASM X-ray luminosity may be determined from Figure 1 as reaching values of $\sim 0.5$ cts/s. This corresponds to a peak luminosities of $\sim 6 \times 10^{35}$ erg/s and is in good agreement with the BeppoSAX value of $8 \times 10^{35}$ erg/s quoted earlier in this paper.

### 4 OPTICAL AND IR PHOTOMETRY

The sources were observed by the SAAO 1.0m telescope in 1996, 1999 and 2000. The exact dates of the individual observations are given in Tables 1 and 2. The data were collected using the Tek8 CCD giving a field of approximately 3 arcmin and a pixel scale of 0.3 arcsec per pixel. Observations were made through standard Johnson UBVRI and Strömgren-Crawford uvbyβ filters. The data were reduced using IRAF and Starlink software, and the instrumental magnitudes were corrected to the standard system using E region standards.

In addition, IR data on RX J0544.1-7100 were obtained from the public archives of the 2MASS survey of the LMC. Though the data were taken about a year before our optical observations, they are included here so that possible IR emission from the circumstellar disk could be investigated. There are no reported IR data on RX J0520.5-6932 in the same catalogue.

All the resulting photometric magnitudes are given in Tables 1 and 2.

The average OGLE values over all their data come from Udalski (private communication). Of course, it is obvious from Figures 1 and 2 that the sources have not been constant and so we should not expect perfect agreement between the OGLE average values and the specific values reported here.

#### Table 1. Optical and IR photometry of the counterpart to RX J0544.1-7100.

| Band | 21 Mar 1998 (2MASS data) | 7 Jan 1999 | OGLE average |
|------|--------------------------|------------|--------------|
| B    | 15.39±0.05               | 15.27      |
| V    | 15.36±0.05               |            |
| R    | 15.26±0.05               |            |
| I    | 15.14                    |            |
| u    | 15.63±0.05               |            |
| v    | 15.45±0.05               |            |
| b    | 15.45±0.05               |            |
| y    | 15.30±0.05               |            |
| J    | 15.18±0.06               |            |
| H    | 14.97±0.09               |            |
| K    | 15.19±0.19               |            |

#### Table 2. Optical and IR photometry of the counterpart to RX J0520.5-6932.

| Band | 4 Oct 1996 | 17 Jan 2000 | OGLE average |
|------|------------|-------------|--------------|
| U    | 14.1±0.1   |             |              |
| B    | 14.44±0.01 |             | 14.39        |
| V    | 14.43±0.01 |             | 14.45        |
| R    | 14.36±0.03 |             |              |
| I    | 14.34      |             |              |
| u    | 14.4±0.1   |             |              |
| v    | 14.55±0.03 |             |              |
| b    | 14.43±0.02 |             |              |
| y    | 14.33±0.02 |             |              |

### 5 OPTICAL SPECTROSCOPY

A red spectrum of RX J0544.1-7100 is shown in Figure 5, was obtained from the 1.9m SAAO observatory on 9 January 1999 using the Cassegrain spectrograph with the SITe2 CCD detector. Though of a low signal-to-noise ratio, the spectrum, clearly shows Hα in emission, though little can be determined about the line shape. The Hα line has an equivalent width of EW = -7±1Å and a central position of 6568±1Å.

Blue spectroscopy of both sources were obtained on 1st November 1999 using the ESO 1.52-m telescope at La Silla Observatory, Chile. The telescope was equipped with the Boller & Chivens spectrograph + #32 holographic
grating. The nominal dispersion for this configuration is \( \sim 0.5 \, \text{Å/pixel} \), while measurements of the FWHM of arc lines indicate a spectral resolution of \( \approx 1.4 \, \text{Å} \) at \( \lambda 4500 \, \text{Å} \). The blue spectra are shown in Figures 6 and 7. For RX J0544.1-7100 the H\(\beta\) line has an equivalent width of \( \text{EW} = -0.20 \pm 0.02 \, \text{Å} \).

6 DISCUSSION

6.1 RX J0544.1–7100

6.1.1 Spectral Class and LMC membership

The spectrum of the optical counterpart to RX J0544.1-7100 in the classification region is displayed in Figure 6, together with that of the B0V standard \( \nu \) Ori. The spectrum of a Be star of similar spectral class is included for comparison. This is HD 161103, given as B0.5III-Ve by Steele et al. (1999).

Though the spectrum of RX J0544.1–700 has a low signal-to-noise ratio, photospheric lines are relatively clear and strong shortwards of \( \sim 4200 \, \text{Å} \). Weak Si\(\text{iv}\) \( \lambda 4089 \, \text{Å} \) and He\(\text{ii}\) \( \lambda 4686 \, \text{Å} \) indicate that the spectral type of RX J0544.1-7100, as in most counterparts to Be/X-ray binaries, is close to B0. Since these lines are weak and He, the Be star. Using the H\(\alpha\) the Be star. Using the H\(\alpha\) as B0V, with an uncertainty of half a spectral subtype (due to the low SNR).

If we assume this spectral class of B0V then we can determine the line of sight extinction to our source from the photometry in Table 1. A star of this spectral type has absolute magnitudes of \( B = -4.3 \), \( V = -4.0 \) and \( R = -3.87 \). The distance modulus to the LMC is 18.5 \( \pm \) 0.2 magnitudes (Westerlund 1997). In order to get agreement between a reddened version of these photometric magnitudes and our observations it is necessary to assume \( E(B-V) = 0.26 \pm 0.06 \). If we also consider the uncertainty of a half sub-class in the spectral type, then this uncertainty could be as large as 0.08. Schuerer & Israel (1991) quote a foreground reddening to the LMC in the range 0.7 to 1.07 and from their Figure 7b it can be seen that RX J0544.1-7100 lies in the region of highest reddening where \( E(B-V) \approx 0.15 \). Our result is consistent within errors with their value. If the reddening to this system proves to be higher than expected then some of this may be accounted for from local circumstellar extinction around the Be star. Using the H\(\alpha\) EW = -7 Å and Equation 5 from Fabregat & Torrejon (1998), we can estimate that \( E^{\text{H\(\alpha\)}}(B-V) = 0.03 \).

Interestingly, the IR photometry presented here from the 2MASS survey indicate more than just a high level of interstellar reddening. The intrinsic (J–K) for a B0V star is \( -0.23 \), where as we have an observed value of -0.01. Using our value of \( E(B-V) = 0.26 \) gives \( E(J-K) = 0.14 \), and hence a predicted observed value of \( (J-K) = 0.09 \). Though the errors on the 2MASS values, especially K, are rather large, there is a suggestion of further reddening in the IR band arising from the presence of a circumstellar disk.

On the question of LMC membership there can be little doubt that this system lies in the LMC. The position of the H\(\alpha\) emission line corresponds to a red shift of 228 \( \pm 45 \, \text{km/s} \), and the redshift of the absorption lines in the blue spectrum to an average value of 220 \( \pm 80 \, \text{km/s} \). Both of these data sets are consistent with LMC membership (for example, Fischer, Welch & Mateo (1993) quote a mean velocity for a cluster in the LMC of 251 \( \pm 2 \, \text{km/s} \)).

6.1.2 X-ray luminosity

6.1.3 Optical variability

It is almost certain that the largest peak in the OGLE power spectrum (at 286d) reflects the global changes taking place in the luminosity. The total data run is only approximately 900d, so it is not really long enough to claim that a \( \sim 300d \) period could be a coherent modulation in any convincing manner. It is much more likely that the fluctuations seen are similar to those seen in other Be stars. Certainly the two relatively deep minima at TJD \( \sim 1290 \) and \( \sim 1600 \) will be providing a lot of the power seen around \( \sim 300d \).

6.2 RX J0520.5-6932

6.2.1 Binary period

The only detection of this source in X-ray has been reported by Schmidtke et al. (1994). Their ROSAT observations were carried out on 11 Feb 1991 which, interestingly, correspond to a binary phase of 0.90 (phase 0.0 has been defined here as the peak optical flux). In addition, Schmidtke et al. (1999) report a non-detection by ROSAT at binary phase 0.58 (22 July 1995). Consequently it is possible that the X-ray flux is modulated in the same manner as the optical, though the evidence so far is rather sparse.

In the case of RX J0520.5-6932 the optical modulation shown in Figure 2 bears a striking resemblance in shape to that seen in A 0538-66 (Densham et al., 1983), but at a much smaller magnitude. In that source the optical outburst reached a value of 2.5 magnitudes above the baseline whereas we only see variations of 0.03 magnitudes. (More recent work by Alcock et al., 2000 has shown that the optical outburst size in A 0538-66 has decreased to 0.4-0.6 magnitudes). Nonetheless the periods are not very different (16.6d in A 0538-66 and 24.4d in our object) and the optical counterparts are both Be stars. Charles et al. (1983) attribute the optical outbursts in A 0538-66 to localised Roche lobe overflow induced by the close passage of the neutron star.

6.2.2 Spectral classification and LMC membership

The spectrum of the optical counterpart to RX J0520.5-6932 in the classification region is displayed in Figure 7, together with that of two standard stars.

As noted by Schmidtke et al. (1994), the photospheric lines are extremely shallow. This is, at least in part, due to the obvious presence of emission components affecting all H\(\alpha\) and He\(\alpha\) lines. H\(\beta\) is in emission with an EW of -0.5 Å, while H\(\gamma\) is completely filled in. It must be pointed out, however, that the He\(\alpha\) and metallic lines where no infilling is expected are also very shallow.

The presence of relatively strong He\(\alpha\) lines clearly identifies the object as an O-type star. In Fig 8, the MK standard stars AE Aur (O9.5V) and 10 Lac (O9V) are also shown as

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comparison. The well-marked Si $\text{iv}$ lines in the wings of H$\beta$ indicate a spectral type close to O9, while their moderate strength and the absence of obvious Si $\text{iii}$ or O $\text{ii}$ lines indicates a main-sequence star. The presence of C $\text{iii}$ $\lambda$ 4650 Å and the strength of the Si $\text{iv}$ lines makes the O8V spectral type proposed by Schmidtke et al. (1994) seem a bit too early. However, the shallowness of the lines makes the spectral classification slightly insecure. We will therefore adopt a spectral type O9V, allowing at the most one spectral subtype uncertainty.

Such a classification is consistent with our photometric measurements and an E(B-V)=0.32 (very similar to the value obtained for RX J0544.1-7100).

Finally from the position of the H$\beta$ line we obtain a red shift of 345±30 km/s which, though a slightly high value, is consistent with LMC membership.

6.3 General remarks

Since the system parameters of these objects seem to indicate a Be/X-ray binary system then the Corbet diagram (Corbet et al, 1999) may be used to estimate the missing timing parameters. For RX J0544.1–7100 we have $P_{\text{pulse}}=96$s and hence a likely $P_{\text{orb}}$ would be just over 100d similar to the well-studied system A0535+26 ($P_{\text{pulse}}=104$s, $P_{\text{orb}}=111$d). In the case of RX J0520.5–6932 we have $P_{\text{orb}}=24.45$d and hence a probable $P_{\text{pulse}}=3$-4s, making it similar to 4U 0115+63 ($P_{\text{pulse}}=3.6$s, $P_{\text{orb}}=24.3$d).

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Figure 6. The blue spectrum of the optical counterpart to RX J0544.1-7100 (middle) compared to that of the B0V standard ν Ori (bottom) and the B0.5e star HD 161103 (top). All spectra have been normalised by division into a spline fit to the continuum and smoothed with a Gaussian filter ($\sigma = 0.8$ Å).

Figure 7. The blue spectrum of the optical counterpart to RX J020.5–6932 (middle) compared to that of the 09.5V standard AE Aur (upper) and the O9V standard 10 Lac (lower). All spectra have been normalised by division into a spline fit to the continuum and smoothed with a Gaussian filter ($\sigma = 0.6$ Å).