The optical counterparts to Be/X-ray binaries in the Magellanic Clouds

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ABSTRACT

The fields of 8 X-ray sources in the Magellanic Clouds believed to be Be/X-ray binaries have been searched for possible Be star counterparts. BV R\text{c} and H\alpha CCD imaging was employed to identify early type emission stars through colour indices and H\alpha fluxes. Spectroscopy of 5 sources confirms the presence of H\alpha emission in each case. Based on the positional coincidence of emission line objects with the X-ray sources, we identify Be star counterparts to the ROSAT sources RX J0032.9-7348, RX J0049.1-7250, RX J0054.9-7226 and RX J0101.0-7206, and to the recently discovered ASCA source AX J0051-72. We confirm the Be star nature of the counterpart to the HEAO1 source H0544-66. In the field of the ROSAT source RX J0051.8-7231 we find that there are three possible counterparts, each showing evidence for H\alpha emission. We find a close double in the error circle of the EXOSAT source EXO 0531.1-6609, each component of which could be a Be star associated with the X-ray source.

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

1 INTRODUCTION

The Magellanic Clouds (MC’s) 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 interest as any differences with the same population in our own Galaxy will have implications on the evolutionary differences of the stars within the galaxies. A High Mass X-ray Binary (HMXB) consists of a compact object (neutron star or black hole) in orbit around a non-degenerate massive (OB type) star. X-ray emission is the result of accretion of material onto the compact object from the massive companion. The HMXB’s can be divided into those with supergiant companions, and those with Be star companions. A Be star is defined as an early type luminosity class III–V star which has at some time shown emission in the Balmer lines. This Balmer emission, along with a significant infrared excess is believed to originate in the circumstellar material which forms a disc around the star. The X-ray emission in these systems is transient in nature, as the orbit is wide and eccentric, and the neutron star passes through the densest regions of the circumstellar disc at periastron only. In the supergiant systems, the companion fills or is close to filling its Roche lobe, and mass transfer occurs through Roche lobe overflow or via a strong stellar wind removing $\sim 10^{-8} M_\odot y^{-1}$. These systems tend to be more persistent than the Be/X-ray binaries, sometimes showing flaring events on short timescales (For a comprehensive review of X-ray binaries, see Lewin, van Paradijs & van den Heuvel 1995.)

Observations of the HMXB’s in the Magellanic Clouds appear to show marked differences in the populations. The X-ray luminosity distribution of the MC 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 (see 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 MC’s, whilst Pakull (1989) refers to evolutionary scenarios of van den Heuvel & Habets (1984) and de Kool et al (1987) which appear to favour black hole formation in low metal abundance environments.

In order to study the differences between the HMXB populations of the Magellanic Clouds and the Galaxy, it is desirable to determine the physical parameters of as many systems as possible. We can then investigate whether the
distributions of mass, orbital period, or spectral type are significantly different. Because of the small sample size of known Be/X-ray binaries in the Magellanic Clouds we have searched the fields of a number of unidentified X-ray sources suspected to be HMXB's in an attempt to identify more Be/X-ray binaries.

Table 1 lists the X-ray sources in the Magellanic Clouds observed during this study. The sample was chosen to include unidentified X-ray sources from which either pulsations have been detected, or other characteristics that strongly suggest a HMXB status.

In Table 1, column 4 gives the uncertainty in X-ray position in arcseconds. Many of the sources are ROSAT detections with uncertainties of the order of a few arcseconds. In galactic fields, sub-ten arcsecond resolution would normally be adequate for an unambiguous optical identification, but owing to the crowded nature of Magellanic Cloud fields, even some of the ROSAT sources have X-ray positional uncertainties that allow several possible optical candidates.

We obtained CCD images of the fields through BV(R)C and Hα filters in order to identify early type stars within the fields, and to search for Hα emission from these stars. We have also obtained medium- and low-resolution spectroscopy of most candidates in order to confirm the presence of Hα emission, and to measure radial velocities to allow confirmation of SMC or LMC membership.

In the following sections we describe in more detail the observations and subsequent analysis, and present resulting data for identified candidates.

2 OBSERVATIONS

2.1 CCD Photometry

CCD imaging was performed at the SAAO during 1996 October 1–7. All observations were made using the 1.0-m telescope and Tek8 CCD, plus 3x Shara focal reducer. The resulting pixel scale was 1.05" per pixel, with a total image size of 519x519". All fields were observed through R and Hα filters. In addition, most fields were observed through B and V filters. The Hα filter used was an interference filter centered on 6562Å, with a width of 50Å. A complete log of observations is shown in Table 2 and finding charts for all the targets are presented in Figure 1.

The use of the focal reducer, whilst necessary to provide a field of view adequate to search larger X-ray error circles, introduced significant vignetting which was not satisfactorily removed by flat-field corrections. Analysis showed that flat-field errors were below the 1% level within 4' of the image centre. In subsequent analysis we therefore rejected any measurements of objects that lay further than 4' from the image centre.

Due to the crowded nature of the fields, profile fitting photometry was necessary. PSF fitting photometry was carried out using IRAF/DAOPHOT. In each field between 30 and 50 stars were used to model the PSF. Instrumental magnitudes were transformed to the standard system using observations of a set of E and F region standards.

A Hα magnitude scale was calibrated by defining the zero point such that a R–Hα index has a value of zero for main sequence, non-emission line stars, and becomes positive for emission line stars.

For each field observed, an emission-colour diagram was plotted, with the R-Hα emission index on the vertical axis, and the B-V colour index on the horizontal axis. As demonstrated by Grebel (1997), when such a diagram is plotted for Magellanic Cloud fields, where all objects lie at the same distance and are affected by the same reddening, Be stars can be clearly distinguished by their blue colour, and high emission index. Comparing photometry of other objects observed during this run with photometry obtained on other occasions without use of the focal reducer indicated that errors of up to 0.1 in magnitude could have resulted from fitting a poorly sampled PSF. In addition, some observations were made in conditions which were slightly below photometric quality, introducing systematic errors. As the method of identification of Be star candidates is through their relative positions in the emission–colour diagram, systematic errors do not undermine our results.

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<td>00 51 53.0</td>
<td>-72 31 45</td>
<td>11</td>
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<td>October 1</td>
<td>Hα</td>
<td>1000</td>
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<tr>
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<td>October 1</td>
<td>R</td>
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<td></td>
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<td>1000</td>
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<tr>
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<td>October 1</td>
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2.2 Optical spectroscopy

Optical spectra were obtained with the 1.9-m telescope at the SAAO and the Cassegrain spectrograph with SITe 1 CCD. On 1998 February 3 and 4 spectra were obtained with a spectral range of 6295–7042 Å and dispersion of 0.43 Å/pixel. On 1998 February 5, low resolution spectra were obtained with a range of 3800–7780 Å, and a dispersion of 2.2 Å/pixel. A log of spectroscopic observations is shown in Table 3. All spectra were reduced using tasks in IRAF’s KPNOsLit package. Spectra were optimally extracted, and wavelength scales were applied using arc-lamp spectra obtained before and after each target observation.

On 1998 February 5, a flux standard was observed, as well as a smooth spectrum standard for the removal of telluric features. All low resolution spectra have subsequently been flux calibrated, and telluric features to the red of Hα have been removed.

Table 3. Log of spectroscopic observations made with the 1.9m telescope at the SAAO (all in 1998)

<table>
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<tr>
<th>Object</th>
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<td>6295 - 7042 Å</td>
<td>0.42 Å/pixel</td>
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<td>900+900</td>
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<td>6295 - 7042 Å</td>
<td>0.42 Å/pixel</td>
</tr>
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<td>EXO 0531.1-6609</td>
<td>Feb 3</td>
<td>900+900</td>
<td>5</td>
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<td>0.42 Å/pixel</td>
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<td>Feb 3</td>
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<td>5</td>
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<tr>
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<td>Feb 4</td>
<td>900+1200</td>
<td>5</td>
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<td>RX J0054.7-226</td>
<td>Feb 4</td>
<td>900+1200</td>
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<td>RX J0054.7-226</td>
<td>Feb 5</td>
<td>300+600</td>
<td>7</td>
<td>3800 - 7779 Å</td>
<td>2.2 Å/pixel</td>
</tr>
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3 RESULTS AND DISCUSSION OF INDIVIDUAL SOURCES

3.1 RX J0032.9-7348

This source was discovered by Kahabka & Pietsch (1996, hereafter KP1996) in ROSAT pointed observations made in 1992 December and 1993 April. The unabsorbed bolometric luminosity they derive from the 1993 observations is 2.5 × 10^{36} ergs s^{-1}, whilst the 1992 December flux was a factor of 6 less. From the X-ray spectrum, length of the X-ray high state (at least 5 days in 1993 April), and long term variability, KP1996 propose a likely HMXB nature for the source. The X-ray position was determined to an accuracy of ± 62 arcseconds (KP1996).

We obtained BVRI and Hα images of the field on the night of 1996 October 1. Figure 2 shows the emission – colour diagram for stars in the field, the left hand plot showing all stars in the field, the right hand plot showing only those stars within a field centered on the X-ray position, with a radius 124 arcseconds (twice the positional uncertainty). On this plot, we further identify those stars that lie within the X-ray error circle by plotting with filled circles. The field population is predominantly evolved red stars, with only six early type stars detected within the 124 arcsecond area. Of these early type stars, two show clear excess Hα flux. The strongest Hα excess is seen from a star which lies within the X-ray error circle (~12 arcseconds from the X-ray position, marked as Object 1 in Figures 1(a) and 1996 October 1.

Our medium resolution spectrum of object 1 (Fig 3(a)) shows Hα in emission with an equivalent width of EW(Hα) = -35 Å. No He I (6678 Å) feature is seen above the level of the continuum noise. The Hα line is single peaked, and centered on 6566.5 ± 0.5 Å. Assuming that the deviation from the rest wavelength of Hα is purely due to the radial velocity of the star, we derive a velocity of 171 ± 23 km s^{-1}, consistent with the systemic radial velocity for the SMC of 166 ± 3 km s^{-1} found by Feast (1961). This object is the most probable optical counterpart for RX J0032.9-7348 (but see the discussion on chance probability in Section 4).

3.2 RX J0049.1-7250

This source was discovered with ROSAT (KP1996) in pointed observations. It appears highly absorbed, and is variable by a factor of more than 10. KP1996 concluded that the source probably lay behind the SMC, with a maximum luminosity of ~ 10^{38} ergs, but they could not rule out a time variable background AGN nature for the source. A new X-ray pulsar was discovered by the RXTE satel-
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Figure 2. Left: Hα emission index versus B – V colour index for objects in the field of the X-ray source RX J0032.9-7348. Right: The same diagram for objects within 124 arcseconds (twice the positional uncertainty) of the ROSAT X-ray position. Objects lying within the error circle are plotted with filled circles.

Figure 3. Hα spectra of the optical counterparts to the X-ray sources. (a) RX J0032.9-7348; (b) AX J0051-722; (c) RX J0051.8-7231; (d) 1WGA J0054.9-7226; (e) RX J0101.0-7321; (f) EXO0531.1-6609; (g) H0544-665.

3.3 AX J0051-722

This source was first detected as a 91.12 second pulsar in RXTE observations (Corbet et al. 1998a) although was initially confused with the nearby 46 second pulsar 1WGA J0053.8-7226 (Buckley et al. 1998). Further observations with ASCA revealed two pulsars in the field with an approximate 2 to 1 ratio in periods, the 91 second period belonging to the new source, AX J0051-722, whilst observations with ROSAT reduced the positional uncertainty to 10 arcseconds. We performed spectroscopic observations of the brightest object in this error circle on 1998 February 3 (see finder chart in Figure 1(c)). The spectrum (Figure 3(b)) shows the Hα line strongly in emission, with an equivalent width of -22 Å. The centre of the line corresponds to a velocity of 165±23 km s⁻¹, consistent with SMC membership.

We have no photometry of objects in this field, but estimate V ∼ 15 from Digitised Sky Survey images. This, together with the Hα emission and radial velocity indicates an early Be star in the SMC. With an X-ray positional uncertainty of only 10 arcseconds, we conclude that this Be star is the optical counterpart to the X-ray pulsar.

3.4 RX J0051.8-7231

RX J0051.8-7231 was discovered in Einstein observations. The X-ray error circle included the bright SMC star AV 111.
with RX J0054.9-7226, and refining the pulse period to 58.969 seconds (Santangelo & Casulano 1998). The uncertainty in X-ray position was further reduced to a 10 arc-second radius from the analysis of archival ROSAT data by Israel (1998).

We obtained $BVR$ and Hα images of the field on the night of 1996 October 5. An emission – colour diagram for the field revealed four objects within the X-ray error circle, all identified as early type stars by their $B$ – $V$ colours. Of these, only one shows strong Hα emission, with $R$-Hα value of 0.49 (the object indicated in Figure 1(e)).

We obtained spectra of Object 1 on the nights of 1998 February 4 and 5. The medium resolution Hα spectrum obtained is shown in Figure 3(d). The Hα line shows strong emission, with an equivalent width of EW(Hα) = −25 ± 2 Å, and a radial velocity of 137 ± 28 km s$^{-1}$, consistent with SMC membership. The low resolution spectrum in Figure 4 shows Hβ also clearly in emission, with EW(Hβ) = −2.0±1.0 Å.

3.6 RX J0101.0-7321

This X-ray source was discovered in ROSAT pointed observations in 1991 October. Observations approximately 6 months later failed to detect the source, suggesting a transient nature (Kahabka & Pietsch 1996). KP1996 claim that the source is most likely associated with a 15-16th magnitude Be star. To the authors’ knowledge, no observations of this star have previously been published.

We only obtained $R_C$ and Hα images of the field of RX J0101.0-7321 on 1995 October 1. A plot of the measured Hα magnitudes against the measured $R_C$–band magnitudes shows a clear linear relationship exists between $R$ and Hα; the scatter at magnitudes $R > 15.5$ is mostly due to uncertainties in the Hα magnitudes. Three points show Hα excesses which appear to be much greater than the local scatter of points. Objects 2 and 3 each lie a few arcminutes from the X-ray position, whilst the error associated with this position is only 11 arcsec. Object 1 is only 10 arcsec from the X-ray position (see the finder chart in Figure 1(f)).

On 1998 February 3 we obtained a Hα spectrum of Object 1. The spectrum, shown in Figure 3(e), has a strong Hα emission line, with EW(Hα)=60 Å. The peak of the Hα line is at a wavelength of 6566.0±0.5 Å, corresponding to a velocity of 148±23 km s$^{-1}$. These data confirm that Object 1 is a Be star in the SMC. As this is the only such object within several arcminutes of the X-ray position, we identify object 1 as the optical counterpart, and confirm a Be/X-ray binary nature for this X-ray source.

3.7 EXO 0531.1-6609

This source was discovered by EXOSAT during deep observations of the LMC X-4 region in 1983 (Pakull et al. 1985). It was detected again in 1985 by the SL2 XRT experiment. The lack of detection in EXOSAT observations made between these dates demonstrates the transient nature of the source. The object was identified with a Be star by Pakull (private communication). The counterpart proposed by Pakull is the northern component of a close double.

The components of this double are marked 1 and 2 in Figures 1(g). The positions of the two objects in the...
emission-colour diagram show that both are early type stars. With our chosen criterion of a Be star having R-H$_\alpha$ ≥ 0.2 then Object 1 is the only Be star within the X-ray error circle, with R-H$_\alpha$ = 0.21. Object 2 has R-H$_\alpha$ = 0.15; within the uncertainties however, our data do not favour one object over another as emission line objects.

On 1998 February 3 we obtained a spectrum of the Northern component of the double. The resulting spectrum shown in Figure 3(f) confirms the presence of H$_\alpha$ emission, with EW(H$_\alpha$) = -10.0 ± 1.0 Å. The line is centered on a wavelength of 6568.7 ± 0.5 Å, corresponding to a velocity of 272 ± 23 km s$^{-1}$. On 1998 February 5 we obtained a low resolution, flux calibrated spectrum of this object (shown in Figure 5), showing H$_\beta$ also in emission with EW(H$_\beta$) = -0.5 ± 0.2 Å. No spectrum has yet been obtained of the Southern component of the double.

In order to determine which object is the counterpart to the X-ray source, it will be necessary to obtain an X-ray position to sub-arcsecond accuracy, possible with the forthcoming AXAF mission, or to find optical/infrared variations in one of the objects which correlate with X-ray behaviour.

### 3.8 H0544-665

This source was discovered with the HEAO-J scanning modulation collimator by Johnston, Bradt & Doxsey (1979). The brightest object within the X-ray error circle (star 1 in Figure 1, and in Figure 6 of Johnston, Bradt & Doxsey 1979) was found to be a variable B0-1 star (van der Klis et al. 1983 and references therein) but no emission lines have been observed in its spectrum to identify it as a Be star. van der Klis et al. (1983) published photometry which showed a negative correlation between optical magnitudes and colour indices, typical of Be stars whose variability is due to variations in the circumstellar disc. The authors expressed concern at the lack of other obvious Be star spectral characteristics, but suggested that the object may be a Be star in a low state of activity.

An emission-colour diagram for objects in the field was created as previously described. In the 4 arcminute radius area searched, only one object displays the colours indicative of a Be star. This object is identified as Object 1 in Figure 1, and corresponds to the Object 1 of Johnson, Bradt & Doxey (1979).

We obtained optical spectra of this object in 1998 February, these are shown in Figures 3(g) and 6. The H$_\alpha$ line is clearly in emission, with an equivalent width measured from the medium resolution spectrum (Figure 3(g)) of EW(H$_\alpha$) = -8.7 ± 1.0 Å. The profile is double peaked with a peak separation of 181 ± 30 km s$^{-1}$. The mean velocity of these peaks is 282 ± 20 km s$^{-1}$, consistent with the LMC velocity of 275 km s$^{-1}$ given by Westerlund (1997), but lower than the 369 ± 42 km s$^{-1}$ measured for Balmer absorption lines in this object by van der Klis et al (1983). The low resolution spectrum in Figure 6 shows also weak H$\beta$ emission with EW(H$\beta$) = -0.7 ± 0.5 Å.

To the authors knowledge, these observations represent the first detection of emission lines in the spectrum of this star. We confirm a LMC Be star nature and, due to the lack of other emission line objects in or near the X-ray error circle, we conclude that this star is the optical counterpart of the X-ray source.

### 4 DISCUSSION

The number of Be/X-ray binary systems known in the Magellanic Clouds is now increased to 12 in the SMC and 7 in the LMC. These numbers compare with 29 known in our own Galaxy. Scaling simply by mass, we should expect the number of Be/X-ray binaries in the LMC and SMC to be 0.1 and 0.01 times the number in the Galaxy respectively. In fact we find, especially in the SMC, what appears at first to be an abnormally large Be/X-ray binary population.

The discrepancy might be explained through consideration of a number of issues:

a) Studies of cluster populations in the SMC have shown a higher proportion of Be stars amongst early type stars than in the Galaxy; this may be due to the effects of metallicity on a radiatively driven wind. If a higher proportion of B type stars in the SMC have circumstellar envelopes, then for a given population of B star/Neutron star binaries, more SMC systems would be accreting X-ray systems.

b) The star formation history of the SMC may have
resulted in a hump in the stellar age distribution such that a higher proportion of SMC stars are of the appropriate age to have evolved into Be/X-ray binary systems. Such a scenario would require an increase in star formation activity $\sim 10^7$ years ago. Supporting evidence for such an effect comes from the HI work of Staveley-Smith et al (1997) who deduce from studies of six expanding shells in the SMC a dynamical age of 5.4Myr. They conclude that there must have been an exceptional degree of coherent star formation throughout the SMC at this time.

The photometric method used to identify Be star candidates has proved successful. In each case where spectroscopic observations have been made, the Be star nature of the object has been confirmed. The strength of this approach is illustrated by Figure 7 which shows the relationship between the measured R–Hα index from photometric data and the EW(Hα) of each object for which both such data were available. There appears to be a direct correlation, with the exception of one possible point – that of RX J0101.0-7321. This seemingly anomalous point may be explained by variability, as the photometric and spectroscopic observations were made over 1 year apart. The indication then is that the Be star counterpart in this system underwent some change between 1996 October and 1998 February, which resulted in a large increase in the amount of circumstellar material.

Apart from this kind of inherent difficulty, this approach is clearly an excellent method for identifying the counterparts to High Mass X-ray Binaries.

In addition, one must be careful when examining so many fields of the chance probability of finding a Be star unrelated to the X-ray source. From the 5 fields presented here, a total of 28 objects were found lying within twice the error circle radius with an Hα index of (R-Hα) $> 0.2$. The total area covered by this sample is 103,000 sq. arcsec. This gives an average Be star rate of almost exactly 1 per sq. arcmin, so clearly one has to be careful when working with arc minute size error circles (i.e. RX J0032.9-7348 in this work). Ultimately, either the error circles have to be reduced by a significant factor, or simultaneous variability observed between the X-ray and the optical/IR band, before definite confirmation of the counterpart is established.

5 CONCLUSIONS

We have identified several X-ray sources with Be stars in the Small Magellanic Cloud and demonstrated a reliable technique for doing so. The exceptionally large number of these systems in the SMC can probably be attributed to an unusually large amount of star formation $\sim 10^7$ years ago.

Acknowledgments

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