Optical counterparts to four X-ray sources in the Small Magellanic Cloud

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ABSTRACT
We report on the spectroscopic and photometric analysis of possible optical counterparts to four X-ray sources in the Small Magellanic Cloud: AX J0049.4–7323, AX J0057.4–7325, RX J0058.2–7321 and RX J0101.1–7206. In the case of the last two, we suggest that the presence of strong Hα emission from previously proposed optical candidates is definite confirmation that these are Be stars. Similarly, we detected strong Hα emission from the optical source identified with RX J0049.7–7323 within the error circle for AX J0049.4–7323 and we conclude that these are one and the same object. We were unable to detect any Hα emission from any of the candidates for AX J0057.4–7325 and the associated photometric analysis was also inconclusive.

Key words: stars: general – Magellanic Clouds – X-rays: binaries.

1 INTRODUCTION

1.1 The Magellanic Clouds

The Magellanic Clouds are a pair of satellite galaxies that are gravitationally bound to our own but that have characteristics differing significantly from each other, and from the Milky Way. Both clouds are relatively low in metal abundances, reflecting their separate and distinct evolutionary development (Matteucci et al. 2002). These differences in chemical composition are likely to be reflected in the properties of different stellar populations. The Small Magellanic Cloud (SMC) is located at a distance of approximately 65 kpc and is centred on a position of RA 1 h, Dec. −73°. It is therefore close enough to be observed with modest ground-based telescopes but at the same time, because of its structural and chemical differences, it provides an opportunity to study the way in which these factors may influence the evolution of other galaxies.

Physical characteristics such as mass distribution, orbital period and spectral type are measurable parameters that are likely to yield useful information in the study of differences between the X-ray binary populations of the Magellanic Clouds and our own Galaxy. To find out whether these differ significantly, it is important to identify the optical counterparts of those X-ray sources that remain unidentified and to study as many systems as possible so as to increase the size of the sample studied to a statistically significant number (Coe & Orosz 2000).

1.2 High-mass X-ray binaries in the SMC

Intensive X-ray satellite observations of the SMC have revealed that it contains an unexpectedly large number of high-mass X-ray binaries (HMXB). These are binary pairs consisting of an early-type star in the spectral range O8–B2 and an accreting neutron star, or, more rarely, a black hole. If the compact object in the binary is a neutron star, it is likely to have a strong magnetic field so that matter that has been gravitationally captured is trapped by the field lines. The gravitational energy of the infalling material is then released in the form of X-rays, which will be observed as pulses as the star rotates. The donor star in the binary pair is likely to be visible in the infrared, optical or ultraviolet, whereas the neutron star can generally only be seen in the X-ray range (Negueruela 1998).

At the time of writing, 34 known or probable sources of this type have been identified in the SMC and they continue to be discovered at a rate of 1–2 yr−1, although only a small fraction of these are active at any one time because of their transient nature. All X-ray binaries discovered so far in the SMC are HMXBs (Coe 2000). Observations of these appear to show marked differences in comparison with the Galactic population. The X-ray luminosity distribution of the Magellanic Cloud sources appears to be shifted to higher luminosities and there also seems to be a higher incidence of sources suspected of containing black holes (Stevens, Coe & Buckley 1999).

1.3 Be/X-ray binaries

HMXBs are divided into two broad classes on the basis of the spectral type of the optical counterpart. The first category includes the supergiant X-ray binaries (SXBs) in which the compact object accretes from an OB supergiant, leading to persistent X-ray emission. The other group comprises the Be/X-ray binaries in which a neutron star orbits an OB star surrounded by a circumstellar disc of variable size and density (Negueruela & Coe 2002). In general, these two subgroups are identified with persistent and transient X-ray sources, respectively.

Most HMXBs belong to the Be class, and all except one in the SMC are in this category. The optical companion stars are early-type
luminosity class III–V, typically of $10–20 \, M_\odot$, which at some time have shown emission in the Balmer series lines. The systems as a whole exhibit significant excess flux at long [infrared (IR) and radio] wavelengths, referred to as the infrared excess. These characteristic signatures and strong Hα line emission are attributed to the presence of circumstellar material in a disc-like configuration (Negueruela 1998; Okazaki & Negueruela 2001).

The mechanisms that give rise to the disc are not well understood, although fast rotation is likely to be an important factor, and it is possible that non-radial pulsation and magnetic loops may also play a part. The disc is thought to consist of relatively cool material, which is intercepted periodically by the compact object in an eccentric orbit, leading to regular X-ray outbursts. Another possibility is that the Be star undergoes a sudden ejection of matter (Negueruela 1998). A common feature of the disc is the so-called global one-armed oscillation: an asymmetric distribution of gas in the disc, which is detected as $V/R$ asymmetry in the Hα line profile (Okazaki 1993). This is a characteristic feature of many Be-type spectra and may be a consequence of variations in orbital velocity and gas density caused by Keplerian motion in an eccentric gas ring. The $V/R$ peak intensity ratios often show cyclic variations ranging from a few yr to several decades and these are ascribed to slow apsidal motion of the gas ring in the gravitational field of the central star (Dachs, Hummel & Hanuschik 1992).

Be/X-ray binaries can present differing states of X-ray activity, varying from persistent low or non-detectable luminosity to short outbursts, the latter usually coinciding with the periastron of the neutron star. The low-luminosity persistent emission is caused by accretion of low-density material that could be wind driven but is more likely to be equatorial outflow beyond the regions in which rotation dominates. Systems with small orbits will tend to accrete from dense regions of the disc over a range of orbital phases and rotation dominates. Systems with small orbits will tend to accrete more likely to be equatorial outflow beyond the regions in which accretion of low-density material that could be wind driven but is neutron star. The low-luminosity persistent emission is caused by assuming that the stars being searched for were in the spectral range BOV–B2V and that the extinction to the SMC was somewhere in the range $0.08 < E(B − V) < 0.25$. The lower value comes from the work of Schwereng & Israel (1991) and the upper value from direct observations of similar Be systems (see, for example, Coe, Haigh & Reig 2000) and includes a local contribution from the circumstellar disc. The limits chosen were $−0.2 < (B − V) < 0.2$.

The second criterion was simply a cut-off in the V-band magnitude at 17.0, again set by assuming the same spectral class range as above projected to the SMC through any reasonable amount of interstellar and circumstellar absorption.

The third criterion, an infrared $(J − K)$ colour index was determined entirely from previous work. Since the circumstellar disc is the single major contributor to the IR flux, the state of the disc defines the size of the IR excess. Previously determined values for $(J − K)$ range from $−0.1$ up to $0.6$, so a limit of $(J − K) < 0.7$ was chosen from these observations.

Optical $r$-Hα colour indices were also computed because a high relative value would indicate the presence of strong Hα. Where the identification of the counterpart is ambiguous, these are shown in the paper. The $R$ and Hα magnitudes were taken from separate SAAO images and both were uncalibrated. Consequently, the absolute values of this index have no useful meaning and no selection criterion has been applied.

### 3 X-RAY SOURCE LOCATION AND OPTICAL COUNTERPART SEARCH

In order to search for possible counterparts to the X-ray sources, a set of three selection criteria were defined. These criteria were partially based upon both the direct observations of other identified counterparts to BeXBs in the SMC and partially based upon the possible range of observational characteristics of Be stars in the SMC.

The first criterion, an optical $(B − V)$ colour index, was obtained by assuming the stars being searched for were in the spectral range BOV–B2V and that the extinction to the SMC was somewhere in the range $0.08 < E(B − V) < 0.25$. The lower value comes from the work of Schwereng & Israel (1991) and the upper value from direct observations of similar Be systems (see, for example, Coe, Haigh & Reig 2000) and includes a local contribution from the circumstellar disc. The limits chosen were $−0.2 < (B − V) < 0.2$.

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### 3.1 AX J0049.4–7323

Ueno et al. (2000) reported an ASCA observation made during 2000 April 11–17, which revealed coherent pulsations of period $755.5 ± 0.6$ s from a new source in the Small Magellanic Cloud. This was designated AX J0049.4–7323 and was located at RA $0^h 49^m 25.2^s$, Dec. $−73° 23′ 17″$ (equinox 2000.0; error radius 1.5 arcsec) (see Fig. 1). The spectrum was characterized by a flat power-law function with photon index 0.7 and X-ray flux $1.1 × 10^{−12}$ erg cm$^{−2}$ s$^{−1}$ (0.7–10 keV). They noted that the possible Be/X-ray binary RX J0049.7–7323 (Haberl & Sasaki 2000), was located within the ASCA error region.

Hα spectroscopy was carried out on 2001 November 7 on the optical source identified with RX J0049.7–7323. Strong Hα emission of equivalent width $−23.7 ± 0.8$ Å was found (Fig. 2). It is noted that the profile of the curve exhibits a distinct double peak. This is consistent with Doppler effects that would be expected from a circumstellar disc viewed in the plane of rotation. There is also definite $V/R$ asymmetry between the peaks. This is compelling evidence for the presence of a Be star and provides further confirmation that this is the correct identification of this Be/X-ray binary.

Optical photometric values for the whole field within, and immediately outside, the ASCA error circle were taken from the 2000...
January observations for the $B$, $V$, $R$ and $H\alpha$ bands. $B$ and $V$ values were calibrated against objects selected from the OGLE data base. $J$ and $K$ values were taken from the 2MASS Survey. $R$ and $H\alpha$ values could not be calibrated. The relevant colour indices for all objects meeting the previously defined criteria are summarized in Table 1. It is noted that the source identified with RX J0049.7–7323 was found to have a $B - V$ value of $0.05 \pm 0.02$ and a $J - K$ value of $0.26 \pm 0.12$. The $V$ and $J$ values were 14.99 and 14.50, respectively. These data do not point conclusively to a single counterpart, and Fig. 1 shows the position of these objects in relation to the ASCA error circle. The size of the white circles is proportional to the uncalibrated $r$-$H\alpha$ values; the bigger the circle the stronger the $H\alpha$.

The presence of strong $H\alpha$ emission from the optical source identified with RX J0049.7–7323 and the asymmetric double peak identifies it as a Be star and points strongly to the conclusion that this is also the optical counterpart of AX J0049.4–7323. However, the possibility remains that one of the other candidates listed in Table 1 may, in fact, be the correct identification because of the large ASCA error circle.

### Table 1. AX J0049.4–7323. Colour indices of optical candidates meeting the selection criteria. The source identified with RX J0049.7–7323 is shown in bold type.

| RA (2000) | Dec. (2000) | $J - K$ | $V$ | $B - V$ | $r$-$H\alpha$ |
|-----------|-------------|--------|-----|--------|-------------|
| 0 49 12.7 | −73 23 34.2 | 0.10 | 13.86 | 0.04 | −0.25 |
| 0 49 12.7 | −73 21 57.1 | 0.34 | 15.81 | −0.01 | 0.34 |
| 0 49 16.2 | −73 22 3.8 | 0.20 | 16.14 | −0.01 | −0.38 |
| 0 49 21.8 | −73 22 6.8 | 0.14 | 14.38 | 0.09 | −0.47 |
| 0 49 23.5 | −73 24 49.0 | 0.27 | 15.62 | 0.02 | −0.47 |
| 0 49 25.8 | −73 23 24.2 | 0.40 | 14.95 | 0.08 | −0.39 |
| 0 49 26.7 | −73 22 54.3 | −0.03 | 16.68 | −0.02 | −0.73 |
| 0 49 27.6 | −73 21 52.0 | 0.20 | 15.55 | −0.04 | −0.28 |
| 0 49 34.4 | −73 22 12.7 | 0.56 | 15.84 | 0.11 | −0.62 |
| 0 49 35.6 | −73 23 15.6 | 0.36 | 16.40 | 0.08 | 0.07 |
| **0 49 42.0** | **−73 23 14.9** | **0.26** | **14.99** | **0.05** | **0.01** |
| 0 49 20.4 | −73 24 45.2 | 0.26 | 16.23 | −0.17 | −0.50 |

### Figure 1. AX J0049.4–7323. Optical candidates meeting the selection criteria. The size of the small white circles around the stars is indicative of the $r$-$H\alpha$ values. The large white circle is the ASCA error region. The image of the field is taken from the 2000 January $V$-band observation.

### Figure 2. Offset normalized profiles of objects showing $H\alpha$ emission. The original data have been smoothed using a Gaussian of $\sigma = 0.5 \text{ Å}$. The velocity scale has been normalized to the recession velocity of the SMC. Curves are offset on the flux scale as follows: RX J0058.2: +0.8, AX J0049.4: +2.2, RX J0101.0: +4.4. The ‘wine bottle’ structure of RX J0101.0–7206 is evidence for the presence of a circumstellar disc observed from close to the axis of rotation. The double-peaked profile of the other two $H\alpha$ lines indicates the presence of an asymmetric disc, viewed from an angle close to the plane of the disc.

### 3.2 AX J0057.4–7325

Torii et al. (2000) reported an ASCA observation made on 2000 April 25–26, which detected coherent pulsations of period $101.45 \pm 0.07 \text{ s}$ from a new source in the Small Magellanic Cloud, designated AX J0057.4–7325 and located at RA $0^h 57^m 27.0^s$, Dec. $−73^\circ 31^\prime 31^\prime\prime$ (equinox 2000.0; error radius 1 arcmin). The spectrum was characterized by a flat power-law function with photon index 0.9 and X-ray flux $2.4 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.7–10 keV). They noted that the ROSAT source, RX J0057.3–7325 (Kahabka et al. 1999) is located within the error region.

Four potential counterparts falling within both the ROSAT and ASCA error circles were identified and designated A, B, C and D (Fig. 3). Spectra were taken at SAAO on 2001 November 10. None of these stars, however, showed identifiable evidence of $H\alpha$ emission above a $2\sigma$ upper limit of $−2.46 \text{ Å}$.

Using the same IR photometric data as the forgoing section (regrettably the OGLE $B - V$ data do not cover this field), only one
candidate (D) met the selection criteria. One other object (labelled E) emerged as a possible candidate within the ROSAT error circle (see Table 2).

Based on the photometric data, Object D therefore emerges as the most likely candidate for this source, although the absence of any detectable Hα emission in the spectrum taken in 2001 November indicates that no strong conclusion can be drawn. It is possible that time variability may account for the fact that Hα was not observed in emission.

3.4 RX J0101.0–7206

The X-ray transient RX J0101.0–7206 was discovered in the course of ROSAT observations of the SMC in 1990 October (Kahabka & Pietsch 1996) at a luminosity of $1.3 \times 10^{36}$ erg s$^{-1}$. The source was seen in outburst for 22 h but half a year later was no longer detectable at a 2σ upper limit luminosity of $4.6 \times 10^{34}$ erg s$^{-1}$.

Hα spectra of the only two clearly visible stars in the error circle were taken on 2001 November 9. These are numbered 1 and 4 on the V-band image (Fig. 5). Object 1 was found to emit Hα of equivalent width $-54.6 \pm 1.3$ Å (Fig. 2). It is noted that the profile is single peaked with a ‘wine bottle’ shape. This is evidence for the detection of a Be star observed from an angle close to the axis of rotation (Slettebak, Collins & Truax 1992). Hα emission above a 2σ upper limit of $-3.1$ Å could not be detected from Object 4, which also failed to meet the photometric criteria.

Figure 4. RX J0058.2–7231. The likely optical counterpart is indicated by the white lines. The image of the field is taken from the 2000 January V-band observation.
Object 1 also met the photometric criteria applied to the objects in previous sections, showing a $B - V$ colour index of $-0.04 \pm 0.02$ and a $J - K$ index of $0.05 \pm 0.26$. The $V$ and $J$ values were 15.74 and 15.55, respectively. Furthermore, this object exhibited the highest $r$-$H\alpha$ value of all the qualifying objects in the image. We therefore conclude that Object 1 is the optical counterpart.

4 DISCUSSION AND CONCLUSIONS

We have confirmed the identification of RX J0049.7–7323 with its presumed optical counterpart. The presence of strong $H\alpha$ emission and the clear double-peak spectrum from this optical source points strongly to the conclusion that it is also the optical counterpart of AX J0049.4–7323, however, the possibility remains that one of the other candidates identified may be the source associated with the latter. From its $(B - V)$ colour we can infer a spectral type in the range B1–3V, assuming the higher extinction limit of $E(B - V) = 0.25$ seen in other similar systems in the SMC. However, because of the uncertain contribution to the extinction by the circumstellar disc, the only reliable way of determining the spectral class of these objects is by obtaining detailed blue spectra.

The absence of any $H\alpha$ emission from any of the candidates for AX J0057.4–7325 prevents a confident identification, although Object D in Fig. 3 emerges as the most likely counterpart.

Similarly, we conclude that the strong $H\alpha$ emission and marked $V/R$ asymmetry of the line profile from the suggested optical counterpart to RX J0058.2–7321 are confirmation that this is a Be star and hence probably the correct identification. From its $(B - V)$ colour index we can infer that it is a B2–3V-type star.

Finally, we conclude that Object 1 in Fig. 5 is the optical counterpart to RX J0101.1–7206. It has a slightly higher $(B - V)$ colour index, suggesting a slightly later spectral type, maybe B3–4V. However, we note that the $H\alpha$ EW was much larger for this source than any of the others and hence the larger circumstellar disc implied could well be further modifying the colour index.

Future blue spectra of these systems from a larger telescope should help establish the correct spectral classification for all of these objects and finally resolve the remaining uncertainties.

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