A radio survey of supersoft, persistent and transient X-ray sources in the Magellanic Clouds

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ABSTRACT

We present a radio survey of X-ray sources in the Large and Small Magellanic clouds with the Australia Telescope Compact Array at 6.3 and 3.5 cm. Specifically, we have observed the fields of five LMC and two SMC supersoft X-ray sources, the X-ray binaries LMC X-1, X-2, X-3 & X-4, the X-ray transient Nova SMC 1992, and the soft gamma-ray repeater SGR 0525-66. None of the targets are detected as point sources at their catalogued positions. In particular, the proposed supersoft jet source RXJ 0513-69 is not detected, placing constraints on its radio luminosity compared to Galactic jet sources. Limits on emission from the black hole candidate systems LMC X-1 and X-3 are consistent with the radio behaviour of persistent Galactic black hole X-ray binaries, and a previous possible radio detection of LMC X-1 is found to almost certainly be due to nearby field sources. The SNR N49 in the field of SGR 0525-66 is mapped at higher resolution than previously, but there is still no evidence for any enhanced emission or disruption of the SNR at the location of the X-ray source.

Key words:
stars : binaries ... radio continuum : stars ... X-rays : stars ... Magellanic clouds

1 INTRODUCTION

Radio synchrotron and X-ray emission, though at opposite ends of the electromagnetic spectrum, are both tracers of high-energy phenomena in astrophysical sources. Thermal X-ray emission clearly demonstrates the existence of material at extremely high temperatures, while radio synchrotron emission originates in the spiralling of highly relativistic electrons around magnetic field lines. It has become increasingly apparent that the behaviour of sources in one energy regime may be correlated with that in another, although the exact mechanism is often unclear. In particular, radio and X-ray emission from compact Galactic X-ray sources are often related. While radio emission from such sources, typically at distances between 1 - 10 kpc, is now relatively routinely detected and monitored, it has yet to be detected from a binary in an extragalactic system. With this in mind, we have searched for radio emission from some of the most powerful X-ray emitters in the nearest external galaxies, the Large and Small Magellanic clouds, at ~ 55 and ~ 60 kpc respectively.

Targets for our survey included most of the Magellanic cloud supersoft X-ray sources, several bright LMC X-ray binaries and other transient systems.

1.1 Supersoft sources

The prototypical supersoft X-ray sources, CAL 83 and CAL 87, were first detected in the Large Magellanic Cloud in 1979-1980 with the Einstein X-ray Observatory (Long, Helfand & Grabelsky, 1981), although later ROSAT observations have considerably enlarged the group (Trümper et al. 1991). The defining characteristics of the supersoft sources are their extremely low X-ray energies and high bolometric luminosities (typically Lbol ~ 10^{38} erg s^{-1} and Tbb ~ tens of eV, where Tbb is the blackbody temperature).

Progress in determining the exact nature of these systems has been hindered by the fact that they are undetectable in the Galactic plane, due to the high level of soft X-ray absorption (e.g. van den Heuvel et al. 1992). Most
currently known systems are therefore optically faint extragalactic objects, predominantly in the Magellanic clouds and M31 (see e.g. Kahabka & Trümper 1996 for a review). Although the term “supersoft source” has been previously applied to a range of objects such as planetary nebula nuclei (Wang 1991) and PG 1159 stars (Cowley et al. 1995), we shall consider here only those objects exhibiting the characteristics of X-ray binaries (e.g. Crampton et al. 1987; Smale et al. 1988; Pakull et al. 1988; Cowley et al. 1990; Pakull et al. 1993).

The model for the SSSs which has gained predominance is that of an accreting white dwarf in a binary system which is undergoing steady nuclear burning on its surface (van den Heuvel et al. 1992). However, it should be noted that models of black hole (Cowley et al. 1990; Crampton et al. 1996) and neutron star accretors (Greiner, Hasinger & Kahabka 1991; Kylafis & Xilouris 1993) also exist. Indeed, one of the systems considered in this paper, RXJ 0509-71, almost certainly contains a neutron star, although, with 2.7 s pulsations (Hughes 1994) and a Be-type secondary star (Southwell & Charles 1996), it is not strictly an archetypal source.

Of the other supersoft objects considered here, RXJ 0513-69 is unique in being the only SSS to exhibit optical jets (Pakull 1994, private communication; Cowley et al. 1996). The source is an X-ray transient which was discovered in outburst during the ROSAT All Sky Survey (Schaeidt, Hasinger & Trümper 1993). The optical spectrum (Pakull et al. 1993; Cowley et al. 1993; Crampton et al. 1996; Southwell et al. 1996) is similar to that of CAL 83, and the two sources have comparable optical magnitudes (V ~ 16 – 17 mag). However, only RXJ 0513-69 exhibits Doppler-shifted components of HeI 4686 and Hβ, with velocities characteristic of the escape speed of a white dwarf (Southwell et al. 1996), implying the presence of a highly-collimated outflow. However, despite the drawing of analogies with SS433, neither this source nor any other supersoft X-ray binary have ever been detected at radio wavelengths.

One of the LMC sources considered here, RX J0550-71, does not yet have an optical counterpart, hence it should be noted that the nature of this object is particularly uncertain.

1.2 Radio emission from X-ray binaries

Radio emission has been detected from approximately 20% of Galactic X-ray binary systems, comprising a neutron star or black hole accreting matter from a more normal companion (e.g. Hjellming & Han 1995). In several cases the emission has been resolved by high-resolution observations into jet-like structures reminiscent of outflows from AGN, and relativistic or near-relativistic velocities inferred (e.g. Fender, Bell Burnell & Waltman 1997 and references therein). It now seems that black hole systems are particularly likely sources of radio emission, whether transient or persistent – in either case the characteristics of the radio emission are mirrored in those of the X-ray emission.

Persistent black hole systems in quiescence appear to have centimetric radio luminosities which agree within a factor two with each other. For example, observations of Cygnus X-1, GX 339-4, 1E1740.7-2942 and GR5 1758-258 are all consistent with a centimetric flux density of ~ 10 mJy at 3 kpc. More transient systems such as Cygnus X-3, GR5 1915+105 and X-ray ‘novae’ such as V404 Cyg, show much more dramatic variability, with measured flux densities from < 1 to > 20000 mJy.

LMC X-1 and LMC X-3, two very luminous black hole candidates may be included in the class of persistent X-ray sources. At a distance of 55 kpc, we would only expect to observe a flux density of a few tens of μJy, by analogy with their Galactic cousins. However, lack of knowledge of their true nature and the chance of catching a rare flaring state makes the observations worthwhile. In the case of LMC X-1 this is particularly so, as Spencer et al. (1997) report the detection of a significant (~ 80 mJy) flux from the field of this source.

LMC X-4 is an X-ray pulsar system, containing a highly magnetised accreting neutron star. Such systems in our Galaxy are found not to be radio-emitters (Fender et al. 1997). LMC X-2 is a low-mass X-ray binary system thought to contain a neutron star. While we considered both these sources far less likely to be detected than LMC X-1 or LMC X-3, they were included in the survey for completeness.

Nova SMC 1992 (Clark, Remillard & Woo 1996) was discovered in archival ROSAT observations of 1992 Oct 1-2 as an extremely bright transient X-ray source. Clark et al. (1996) proposed a nearby 14th magnitude blue star as the optical counterpart, and suggested the source may be the first high-mass black hole X-ray nova detected. While previous X-ray ‘novae’ have often been very bright radio sources (see above), they are also generally associated with low-mass companion stars and the nature of this system remains uncertain.

1.3 SGR 0525-66

SGR 0525-66 is one of a group of only three confirmed (Smith 1997) and one possible additional (Hurley et al. 1997) soft γ-ray repeaters. These are sources of repeated bursts of low-energy γ-rays, possibly associated with neutron stars. SGR 0525-66 is coincident in the sky with the SNR N49, and a soft X-ray counterpart has been found (Rothschild, Kulkaerni & Lingenfelter 1994). No radio, optical or infrared counterpart has been identified however (Dickel et al. 1995), although Rothschild et al. (1994) predicted a compact plerion-like radio nebula to be associated with the source. Any physical link with N49 has yet to be established.

2 OBSERVATIONS

Observations of the target sources were made between 1997 June 30 and July 13 with the Australia Telescope Compact Array. The array was in the 6D configuration, with baselines ranging between 153 and 6000 m. All observations were made simultaneously at 6.3 and 3.5 cm, except for the RXJ 0513-69 field, which was also observed at 20 & 13 cm, on July 13. Primary flux calibration was achieved in all cases using PKS 1934-638; phase calibration was achieved using calibrators 0515-674 and 0252-712 for the LMC and SMC fields respectively. Observations typically involved 5 min on a nearby phase calibrator followed by 25 min on-target, repeated over a 12-hr run (though less time was spent on LMC X-1, X-2, X-3 and X-4). Data reduction was performed us-
Table 1. Radio survey of Magellanic Cloud X-ray sources with the Australia Telescope compact array. All upper limits are 3σ.

| Source          | Object type                      | Point-source flux density (mJy) |
|-----------------|----------------------------------|-------------------------------|
| RXJ 0513-69     | LMC supersoft source             | < 0.09                        |
| RXJ 0528-69     | LMC supersoft source             | < 0.09                        |
| CAL 83          | LMC supersoft source             | < 0.12                        |
| CAL 87          | LMC supersoft source             | < 0.12                        |
| RXJ 0550-71     | LMC supersoft source             | < 0.15                        |
| LMC X-1         | BHC X-ray binary                 | 1.5                           |
| LMC X-2         | X-ray binary                     | 0.15                          |
| LMC X-3         | BHC X-ray binary                 | 0.12                          |
| LMC X-4         | X-ray pulsar X-ray binary        | 0.15                          |
| SGR 0525-66     | Soft γ-ray repeater              | 0.3                           |
| 1E 0035-72      | SMC supersoft source             | < 0.12                        |
| RXJ 0059-71     | SMC supersoft source             | < 0.12                        |
| Nova SMC 1992   | SMC X-ray transient              | < 0.18                        |

3.2 X-ray binaries

3.2.1 LMC X-1 and LMC X-3

Neither of these two black hole candidates were detected to levels consistent with analogy to their Galactic counterparts. At a distance of 55 kpc, the persistent Galactic radio-emitting X-ray binaries would only be observed at a level of \( \sim 0.05 \) mJy, at about the noise level for LMC X-3, and well below it for LMC X-1.

The noise level in the LMC X-1 observations is far higher than that for the other fields observed; this is due to it residing along a very radio-bright line of sight in the LMC. The source lies at the edge of the bright HII region N149, and in addition there are numerous confusing sources at a level of several tens of mJy or brighter (see e.g. Chu et al. 1997). The possible radio detection of this source noted by Spencer et al. (1997) in their southern hemisphere radio survey of X-ray binaries was almost certainly due to the two radio sources 0540-697 and 0539-697, previously catalogued by Wright et al. (1994), and indicated in Fig 1. Gaussian fits.
Figure 2. 6.3 cm radio map of the SNR N49, with the X-ray location of SGR 0525-66 (Rothschild et al. 1994) indicated as a 5 arcsec radius circle. There is no evidence for enhanced radio emission, nor disruption of the SNR, at the position of SGR 0525-66. Contours are at -3, 3, 6, 9, 12, 16, 20 and 24 times 0.1 mJy. The synthesised beam is $2.30 \times 1.96$ arcsec (p.a. -33°) and is indicated in the lower right corner of the map. The map was created with a robust factor of 0.5 and 5000 CLEAN iterations with a loop gain of 0.1.

3.2.2 LMC X-2 and LMC X-4

The lack of detection of these two sources is again unsurprising. In particular, as noted above, we do not expect to observe radio emission from an X-ray pulsar system whatever the distance.

3.2.3 Nova SMC 1992

The lack of detection of this source is not surprising, nearly four years after its ‘X-ray nova’ outburst, as most X-ray transients return to radio quiescence within a year or so of outburst.

3.3 SGR 0525-66

An image of the field of SGR 0525-66 at 6.3 cm is shown in Fig 2, with the location of the source at the upper bound of the N49 SNR indicated. Details of the map derivation are given in the figure caption. While having poorer $u$-$v$ coverage than the maps of Dickel et al. (1995), our map is sensitive to higher-resolution features. The relatively high 3σ point-source upper limit reflects a high brightness background due to the SNR. In agreement with Dickel et al. (1995) we find neither enhanced point-source emission at the location of the SGR, nor any evidence for disruption of the SNR either at its location or in a path extending back to the core.

It should be stressed that these observations are sensitive only to structures on arcsecond scales, and are resolving out much of the emission from the SNR on arcmin and larger angular scales. Nevertheless, the prediction of Rothschild et al. (1994) that SGR 0525-66 should have an associated compact $(\lesssim 0.3$ arcsec) synchrotron nebula can be tested. The X-ray point source that they have detected with ROSAT has an X-ray luminosity of $\sim 10^{36}$ erg s$^{-1}$. Using the ratio of X-ray to radio luminosities of 1 - 300 established in e.g. Helfand & Becker (1987) for synchrotron nebulae, we would expect a radio luminosity $\geq 10^{33}$ erg s$^{-1}$ if the origin of the X-ray emission is indeed a nonthermal compact synchrotron nebula, or ‘plerion’. However, even at the distance of the LMC (which we here assume to be 55 kpc), our radio observations place limits on the radio luminosity of an associated synchrotron nebula of around $5 \times 10^{31}$ erg s$^{-1}$, significantly below that which would be expected for a plerion. Hence these radio observations cast doubt upon the speculation of Rothschild et al. (1994), as did the earlier observations of Dickel et al. (1995).
4 CONCLUSIONS
We have surveyed the fields of eight LMC and SMC supersoft X-ray sources, the X-ray binaries LMC X-1, X-2, X-3 & X-4, and the soft $\gamma$-ray repeater SR 0525-66 at radio wavelengths. We have found no point-source radio emission from any of the sources. In particular we find no detectable radio emission from the proposed jet source RXJ 0513.9-6951. Neither do we detect nebulosity, such as that observed optically around CAL83, associated with any of the supersoft sources.

Limits on emission from the black hole candidate X-ray binaries LMC X-1 and LMC X-3 are consistent with the radio brightnesses of their Galactic analogues. We show that a possible previous radio detection of LMC X-1 was almost certainly due to nearby field sources, and that due to its location in a radio-bright part of the LMC, this source is going to be very difficult to ever detect. Limits on radio emission from the other two X-ray binaries are as expected.

The SNR N49, which SGR 0525-66 appears to lie on the northern edge of, shows no enhanced emission at the location of the SGR, nor any disruption to its structure suggesting association between the two. We can constrain the radio luminosity of any compact (arcsec-scale) structure associated with the SGR to be more than an order of magnitude below that which we might expect if the X-ray source discussed in Rothschild et al. (1994) were indeed a synchrotron nebula powered by the SGR.

In summary, we have placed limits on radio emission from a variety of X-ray sources in the Magellanic Clouds, finding none of them to be anomalously bright by comparison with the Galactic counterparts. The detection of radio emission from extragalactic X-ray binaries and related systems is likely to require an increase in the sensitivity of ground-based arrays or coordinated and fortunate observations during an outburst.

ACKNOWLEDGEMENTS
We are happy to acknowledge assistance with the observations by Vince McIntyre, and useful discussions with Ralph Spencer. We also thank the referee, David Helfand, for useful suggestions which improved the paper. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

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