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## TRANSIENT RADIO EMISSION FROM SAX J1808.4–3658

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### ABSTRACT

We report on the detection of radio emission from the accretion-powered X-ray millisecond pulsar SAX J1808.4–3658, using the Australia Telescope Compact Array. We detected an  $\sim 0.8$  mJy source at the position of SAX J1808.4–3658 on 1998 April 27, approximately 1 day after the onset of a rapid decline in the X-ray flux; no such source was seen on the previous day. We consider this emission to be related to the radio emission from other X-ray binaries, and it is most likely associated with an ejection of material from the system. No radio emission was detected at later epochs, indicating that if SAX J1808.4–3658 is a radio pulsar during X-ray quiescence, then its monochromatic luminosity must be less than  $L_{1.4\text{ GHz}} \sim 6$  mJy kpc<sup>2</sup>.

*Subject headings:* accretion, accretion disks — binaries: close — pulsars: individual (SAX J1808.4–3658) — radio continuum: stars — stars: neutron

### 1. INTRODUCTION

Millisecond pulsars (MSPs) have long been thought to be the endpoint in the evolution of low-mass X-ray binaries (LMXBs) (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). Although the link between LMXBs and MSPs is strong, evidence that LMXBs did indeed contain objects spinning at millisecond periods was, until recently, still missing. The quasi-periodic oscillations, especially near 1 kHz (van der Klis et al. 1996), recently discovered in X-ray binary systems offer indirect evidence for the existence of weakly magnetized neutron stars with millisecond periods. However, the recent discovery of 2.49 ms coherent X-ray pulsations from the LMXB SAX J1808.4–3658 (Wijnands & van der Klis 1998b; Chakrabarty & Morgan 1998) now gives strong support to the picture that LMXBs are the progenitors of MSPs; this system provides the best evidence yet that a low-field neutron star can be spun up to millisecond periods via accretion from its companion.

There are a number of processes that could potentially produce radio emission from such a system. An exciting possibility is that SAX J1808.4–3658 will, at some point, turn on as a radio pulsar, producing pulsed radio emission characteristic of MSPs. The timing of such pulses could allow an improved determination of the astrometric, rotational, and orbital parameters of the system as well as the determination of possible post-Keplerian and tidal effects. Furthermore, they could probe any wind produced by the interaction between the pulsar and its companion, such as in the eclipsing binary millisecond pulsar systems (e.g., Fruchter et al. 1990). Such emission could potentially be heavily scattered by this interaction or by interactions with material excreted from the system (e.g., Rasio, Shapiro, & Teukolsky 1989). Thus, it would appear unpulsed and could only be detected as a continuum source. Alternatively, unpulsed radio emission could be produced by the interaction of the relativistic pulsar wind with the interstellar medium (e.g., Frail et al. 1996). Finally, radio emission could

be associated with the accretion process and an X-ray outburst, as seen in a significant fraction of the X-ray binary population (Hjellming & Han 1995; Fender & Hendry 1999).

Here we report on a search for radio emission during the outburst and then also during quiescence, and this is aimed at testing these possibilities. In § 2 we describe our observations and analysis, while in § 3 we demonstrate the detection of radio emission from the system and discuss its implications.

### 2. OBSERVATIONS AND REDUCTION

All observations were made with the Australia Telescope Compact Array (ATCA; Frater, Brooks, & Whiteoak 1992), which is an east-west synthesis array located near Narrabri, NSW, Australia; these observations are summarized in Table 1. The ATCA can observe two frequencies simultaneously; for all epochs except 1998 November 30, we alternated, approximately every 20 minutes, between observing with a 1.4/2.5 GHz combination and observing with a 4.8/8.6 GHz combination. On 1998 November 30, observations were only made at 1.4/2.5 GHz. A bandwidth of 128 MHz was used at each frequency. A pointing center, R.A. (J2000) = 18<sup>h</sup>08<sup>m</sup>13<sup>s</sup>, decl. (J2000) =  $-36^{\circ}57'18''$ , was observed in all cases, approximately 3' from the position of SAX J1808.4–3658 (Giles, Hill, & Greenhill 1999). Amplitudes were calibrated using observations of PKS B1934–638, assuming flux densities for this source of 15.0, 11.1, 5.8, and 2.8 Jy at 1.4, 2.5, 4.8, and 8.6 GHz, respectively (where 1 Jy =  $10^{-26}$  W m<sup>-2</sup> Hz<sup>-1</sup>). Phases were calibrated using observations once per hour of PKS B1934–638 (at 1.4 and 2.5 GHz) and PMN J1733–3722 (at 4.8 and 8.6 GHz).

Data were reduced in the MIRIAD package using standard techniques. For each frequency in each observation, images were formed using natural weighting and excluding baselines shorter than 1.5 km. Sidelobes around detected sources were deconvolved using the CLEAN algorithm. Each image was then smoothed to the appropriate diffraction limit and corrected for the mean primary-beam response of the ATCA antennas.

### 3. RESULTS AND DISCUSSION

The position for SAX J1808.4–3658, as determined by observations of its optical counterpart, is at R.A. (J2000) = 18<sup>h</sup>08<sup>m</sup>27<sup>s</sup>.54, decl. (J2000) =  $-36^{\circ}58'44''.3$  with uncertainties of  $\sim 0''.8$  in each coordinate (Giles et al. 1999). In all obser-

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TABLE 1  
ATCA OBSERVATIONS OF SAX J1808.4–3658

| Observation | Date (1998) | Time on Source (hr) | Frequency (GHz) | Resolution (arcsec) | rms (mJy beam <sup>-1</sup> ) |      |
|-------------|-------------|---------------------|-----------------|---------------------|-------------------------------|------|
| 1 .....     | Apr 27      | 4.5                 | 1.4             | 13.0 × 7.2          | 0.22                          |      |
|             |             |                     | 2.5             | 7.3 × 3.8           | 0.21                          |      |
|             |             |                     | 4.8             | 4.3 × 1.6           | 0.15                          |      |
|             |             |                     | 8.6             | 2.1 × 0.8           | 0.18                          |      |
| 2 .....     | May 28      | 11                  | 1.4             | 11.3 × 6.6          | 0.42                          |      |
|             |             |                     | May 30          | 2.5                 | 6.2 × 3.5                     | 0.19 |
|             |             |                     | Jun 1           | 4.8                 | 3.2 × 1.6                     | 0.11 |
| 3 .....     | Jun 10      | 2.5                 | 1.4             | 13.6 × 6.0          | 0.81                          |      |
|             |             |                     | 2.5             | 7.6 × 3.1           | 0.32                          |      |
|             |             |                     | 4.8             | 4.4 × 1.3           | 0.19                          |      |
|             |             |                     | 8.6             | 2.1 × 0.7           | 0.20                          |      |
| 4 .....     | Oct 5       | 9                   | 1.4             | 13.0 × 8.2          | 0.19                          |      |
|             |             |                     | 2.5             | 7.2 × 4.6           | 0.16                          |      |
|             |             |                     | 4.8             | 3.7 × 2.5           | 0.07                          |      |
|             |             |                     | 8.6             | 2.1 × 1.7           | 0.10                          |      |
| 5 .....     | Nov 30      | 6.5                 | 1.4             | 13.5 × 7.2          | 0.12                          |      |
|             |             |                     | 2.5             | 7.5 × 4.0           | 0.10                          |      |

vations except observation 1, the only radio source detected in a  $\sim 5'$  region surrounding this position was a double-lobed radio galaxy, NVSS 180824–365813 (Condon et al. 1998); no source was seen at the position of SAX J1808.4–3658. The resolution and limiting sensitivity for these nondetections are summarized in Table 1.

In observation 1, an unresolved radio source near the position of SAX J1808.4–3658 was detected at the  $\sim 4\sigma$  level at each of the 2.5, 4.8, and 8.6 GHz images, as shown in Figure 1; flux densities are given in Table 2. The source was not detected at 1.4 GHz. We attempted various approaches to the imaging, deconvolution, and fitting processes. The results of these processes suggest a systematic uncertainty in the flux densities for the source of  $\sim 50\%$ , a value that is to be expected when deconvolving a weak source under conditions of poor  $u$ - $v$  coverage. Our best position for this source is R.A. (J2000) =  $18^{\text{h}}08^{\text{m}}27^{\text{s}}.6$ , decl. (J2000) =  $-36^{\circ}58'43''.9$  with an uncertainty of  $\sim 0''.5$  in each coordinate. In the bottom panel of Figure 1, our position and the optically determined positions of Giles et al. (1999) and Roche et al. (1998) are compared. All three positions are consistent within the quoted uncertainties.

The source shown in Figure 1 is almost certainly not an artifact. It is not at the phase center, and it was detected at three different frequencies and for a variety of different weighting schemes and combinations of baselines. While the probability of finding an unrelated radio source within a few arcseconds of SAX J1808.4–3658 is low in any case, we note that this source was not detected at any other epoch, despite the improved sensitivity of these later observations. Furthermore, the region was observed with the Very Large Array (VLA) on 1998 April 26, the day immediately before observation 1, and no source was detected at this position down to a comparable sensitivity (R. M. Hjellming 1999, private communication). Therefore, from its transient nature and positional coincidence with the optical counterpart of SAX J1808.4–3658, we conclude that this radio source is associated with the system.

Our data lack the time resolution required to search for pulsed radio emission from this source. However, X-ray emission due to accretion was present at the time of our detection, and it is likely that if any radio emission was being produced in the pulsar magnetosphere, it would be quenched by this process. Thus, the source we have detected is most likely not

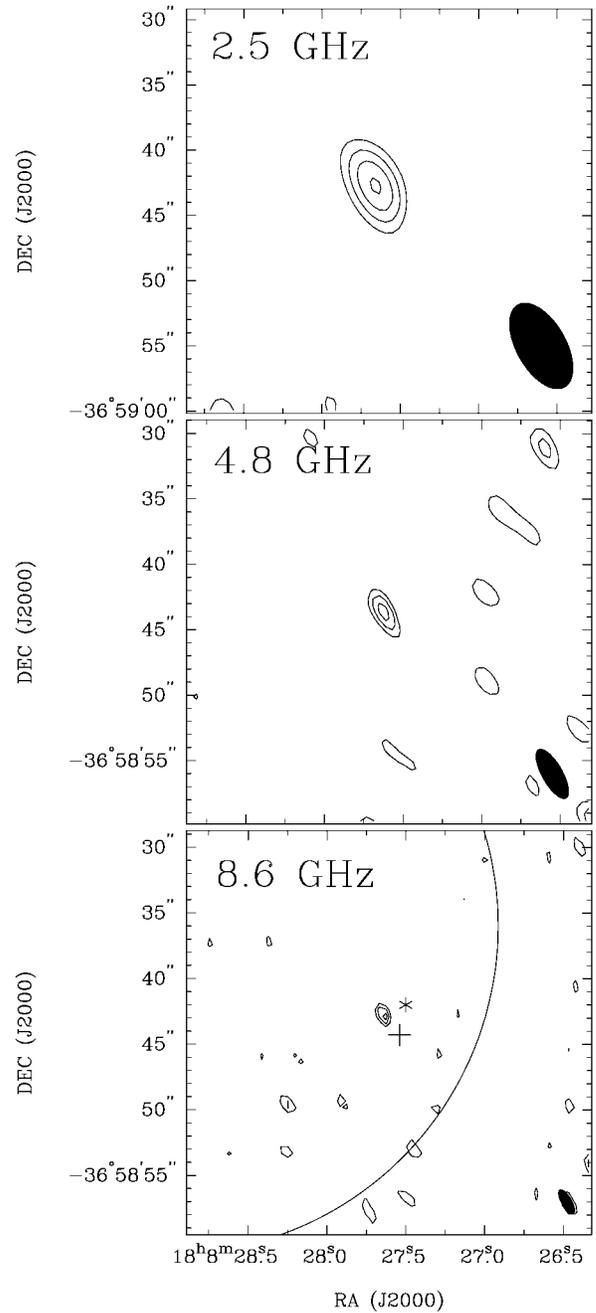


FIG. 1.—The 2.5, 4.8, and 8.6 GHz images of SAX J1808.4–3658 on 1998 April 27. The contours in each image are at the levels of 0.3, 0.45, 0.6, and 0.75 mJy beam<sup>-1</sup>, while the synthesized beam (FWHM) is shown at the lower right-hand corner of each panel. In the 8.6 GHz image, a cross and an asterisk mark the optical positions for SAX J1808.4–3658 of Giles et al. (1999) and Roche et al. (1998), respectively, while the large arc corresponds to the edge of the X-ray-timing error circle of Chakrabarty & Morgan (1998).

TABLE 2  
RESULTS OF OBSERVATION 1

| Frequency (GHz) | Flux of Source (mJy) |
|-----------------|----------------------|
| 1.4 .....       | ...                  |
| 2.5 .....       | 0.8                  |
| 4.8 .....       | 0.8                  |
| 8.6 .....       | 0.8                  |

emission associated with the magnetosphere. It is also unlikely that the source corresponds to emission from a pulsar wind (if such a wind even exists at this point in the system's evolution)—if we assume that the disappearance of the source between observation 1 and observation 2 is due to synchrotron losses, then this cooling timescale implies a magnetic field in the wind of  $\geq 2$  G, which is many orders of magnitudes higher than observed for other pulsars (e.g., Manchester, Staveley-Smith, & Kesteven 1993; Frail et al. 1996). The detection of radio emission only at an epoch during which X-rays were still being generated provides strong evidence that this radio source is related to the accretion process.

Radio emission has been detected from  $\sim 25\%$  of all X-ray binaries (Fender & Hendry 1999). In cases for which this emission has been resolved, it takes the form of jets being emitted from the system, often at relativistic velocities (Fender, Bell Burnell, & Waltman 1997). The burst properties and rapid X-ray variability of SAX J1808.4–3658 suggest that it is an atoll source, i.e., a low magnetic field neutron star accreting at about 10% of the Eddington limit (Wijnands & van der Klis 1998a). Fender & Hendry (1999) review the radio properties of different types of persistent X-ray binaries and show that most atoll sources show no radio emission—the only detections have been transient and at the millijansky level. When transient radio emission is seen from the atoll sources, the spectrum is first seen absorbed, but then it becomes optically thin and takes on a synchrotron spectrum with  $\alpha \approx -0.5$  ( $S_\nu \propto \nu^\alpha$ ). The emission then decays away through adiabatic losses (e.g., Hjellming & Han 1995).

The properties of the radio emission seen here for SAX J1808.4–3658 are consistent with this behavior. While the spectrum of the source is very poorly constrained by our data, the flux densities for it at 2.5 GHz and above are consistent with  $\alpha \approx -0.5$ , while the nondetection at 1.4 GHz is suggestive of a low-frequency turnover that is probably due to self-absorption in the ejecta.

We note that on 1998 April 26, the day before our radio detection, the X-ray flux suddenly deviated from exponential decay and began to decrease rapidly (Gilfanov et al. 1998). As discussed by these authors, there are two different mechanisms that can produce such a cutoff, either the onset of the so-called “propeller phase” or an instability of the accretion disk. In both cases, the abrupt change corresponds to the ejection of material from the system. The appearance of transient radio emission just after this event suggests that it is this ejection of material that has produced the source we see here. If we assume that emission above 2.5 GHz corresponds to optically thin, incoherent, unbeamed, synchrotron emission, the  $10^{12}$  K Compton

limit on the brightness temperature corresponds to a minimum scale for the emission of  $\sim 12$  lt-s at a distance of 4 kpc, which is much larger than the  $\sim 1$  lt-s binary separation of the orbit (Chakrabarty & Morgan 1998). Thus, the emission is coming from well beyond the binary, as would be expected if it has resulted from an expulsion of material from the system.

At later times, no radio emission was detected at the position of SAX J1808.4–3658. This does not necessarily indicate that the radio pulse mechanism is not yet functioning. Despite strong limits on the flux density from our nondetections, the apparently large distance to the system of  $\sim 4$  kpc corresponds to a  $3\sigma$  monochromatic luminosity limit of  $L_{1.4\text{ GHz}} \sim 6$  mJy kpc<sup>2</sup>, which is greater than that of the majority of known MSPs (J. H. Taylor et al. 1995, unpublished).<sup>6</sup> Furthermore, Ergma & Antipova (1999) have proposed that this system may only be detected at shorter wavelengths ( $\lambda < 3$  cm) because of the free-free absorption by material excreted from the system.

#### 4. CONCLUSION

We have detected a transient radio source coincident with SAX J1808.4–3658; the source turned on within a day and then disappeared again a month later. We interpret this source as radio emission associated with the ejection of material, as seen in other X-ray binaries, and in this case possibly associated with the onset of a propeller phase or a disk instability the day before the source was detected. The spectrum and light curve of this source are essentially unconstrained, however, and the source should certainly be searched for radio emission the next time it is in outburst. Eventually, it is hoped that this source will emerge as a radio MSP; radio searches in quiescence should continue to be carried out in anticipation of this.

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<sup>6</sup> Available at <ftp://pulsar.princeton.edu/pub/catalog>.

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