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Fronefield Crawford

Duncan R. Lorimer

Brian M. Devour

Brian P. Takacs

Vladislav I. Kondratiev

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UPPER LIMITS ON PULSED RADIO EMISSION FROM THE 6.85 s X-RAY PULSAR XTE J0103–728 IN THE SMALL MAGELLANIC CLOUD

FRONEFIELD CRAWFORD¹, DUNCAN R. LORIMER², BRIAN M. DEVOUR¹, BRIAN P. TAKACS¹, AND VLADISLAV I. KONDRATIEV^{2,3,4}

¹ Department of Physics and Astronomy, Franklin and Marshall College, P.O. Box 3003, Lancaster, PA 17604, USA; fcrawfor@fandm.edu

² Department of Physics, West Virginia University, Morgantown, WV 26506, USA

³ National Radio Astronomy Observatory, P.O. Box 2, Green Bank, WV 24944, USA

⁴ Astro Space Center of the Lebedev Physical Institute, Profsoyuznaya str. 84/32, Moscow 117997, Russia

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ABSTRACT

X-ray pulsations with a 6.85 s period were recently detected in the Small Magellanic Cloud (SMC) and were subsequently identified as originating from the Be/X-ray binary system XTE J0103–728. The recent localization of the source of the X-ray emission has made a targeted search for radio pulsations from this source possible. The detection of pulsed radio emission from XTE J0103–728 would make it only the second system after PSR B1259–63 that is both a Be/X-ray binary and a radio pulsar. We observed XTE J0103–728 in 2008 February with the Parkes 64 m radio telescope soon after the identification of the source of X-ray pulsations was reported in order to search for corresponding radio pulsations. We used a continuous 6.4 hr observation with a 256 MHz bandwidth centered at 1390 MHz using the center beam of the Parkes multibeam receiver. In the subsequent data analysis, which included a folding search, a Fourier search, a fast-folding algorithm search, and a single pulse search, no pulsed signals were found for trial dispersion measures (DMs) between 0 and 800 pc cm⁻³. This DM range easily encompasses the expected values for sources in the SMC. We place an upper limit of ~45 mJy kpc² on the luminosity of periodic radio emission from XTE J0103–728 at the epoch of our observation, and we compare this limit to a range of luminosities measured for PSR B1259–63, the only Be/X-ray binary currently known to emit radio pulses. We also compare our limit to the radio luminosities of neutron stars having similarly long spin periods to XTE J0103–728. Since the radio pulses from PSR B1259–63 are eclipsed and undetectable during the portion of the orbit near periastron, repeated additional radio search observations of XTE J0103–728 may be valuable if it is undergoing similar eclipsing and if such observations are able to sample the orbital phase of this system well.

Key words: Magellanic clouds – stars: emission-line, Be – stars: neutron – X-rays: binaries

1. INTRODUCTION

Neutron stars appear as detectable sources in a variety of forms. Of the almost 1800 pulsars that are currently known in the Australia Telescope National Facility (ATNF) pulsar catalog (Manchester et al. 2005),⁵ the vast majority are detectable only as radio sources. However, some of these neutron stars are visible as both pulsed X-ray and radio sources, and some pulsars emit pulsed radiation only at high energies (X-rays or gamma rays). A small number of pulsars are also visible at optical wavelengths. Apart from these generally persistent sources, transient radio emitters may also exist in large numbers (McLaughlin et al. 2006), and some neutron stars are known to be transient X-ray sources. For instance, radio pulsations from anomalous X-ray pulsars (AXPs) undergoing X-ray outbursts have recently been detected (Camilo et al. 2006, 2007), while radio emission from several other AXPs has not (Burgay et al. 2006b; Crawford et al. 2007). These results have been used in part to study the physics of this class of highly magnetized neutron stars (“magnetars”). The absence of detectable radio emission in searches of central compact objects (Pavlov et al. 2002; de Luca 2008), nearby thermal X-ray pulsars having long periods (X-ray dim isolated neutron stars (XDINs); e.g., Brazier & Johnston 1999; Johnston 2003; Kondratiev et al. 2008, 2009), and the magnetar-like (i.e., young, having a strong magnetic field, and exhibiting X-ray outbursts) X-ray pulsar PSR J1846–0256 (Archibald et al. 2008) suggests that the emission physics of neutron stars

and the connection between typical radio pulsars and these other kinds of objects are in many ways not well understood. Like some of these X-ray systems, radio pulsars can have long spin periods, but these radio pulsars usually have surface magnetic field strengths that are more typical for the radio pulsar population. PSR J2144–3933 is such an example: it is detectable only as a low-luminosity radio source, has a very long spin period (8.5 s), and has a very small pulsed duty cycle (Young et al. 1999), which suggests that these kinds of systems may be more common than is observed but are easily missed. In short, the study of neutron star systems at multiple wavelengths can provide different windows into the physics of these objects, so a multiwavelength approach is fruitful whenever possible.

Pulsars that are members of binary systems are particularly useful as physical probes, allowing an investigation of the companion star, the pulsar itself, the dynamics and evolution of the system, and theories of gravity. An extensive review is presented by Lorimer (2008). A particular class of high-mass X-ray binary (HMXB) consists of a neutron star orbiting a Be star, which is an early-type nonsupergiant star with observable emission lines from the material in its circumstellar disk (see Slettebak 1988 for a review). Only one Be/X-ray binary is known to also be a radio pulsar: PSR B1259–63 (Johnston et al. 1992). PSR B1259–63 has been extensively studied as both a radio pulsar and a transient X-ray source since its discovery almost 20 years ago, particularly at or near its periastron passages, which occur every 3.4 years (e.g., Kaspi et al. 1995; Johnston et al. 1996, 1999, 2005).

⁵ <http://www.atnf.csiro.au/research/pulsar/psrcat/>.

X-ray pulsations with a period of $6.8482(7)$ s⁶ were first detected by *RXTE* in 2003 May from an unlocalized and unidentified source in the Small Magellanic Cloud (SMC; Corbet et al. 2003). More recently, Haberl & Pietsch (2008) announced the detection of an X-ray transient source in an *XMM-Newton* observation from 2006 October in which these pulsations were again clearly detected. In this latter observation, the pulse period was constrained to be $6.85401(1)$ s, and the source was localized to the position $\alpha = 01:02:53.9$, $\delta = -72:44:34.6$ (J2000), with a position uncertainty of $\sim 1''$. This tight position constraint unambiguously identified the source as the Be/X-ray binary XTE J0103–728, one of the many HMXBs of this type in the SMC (Haberl & Pietsch 2008). Given the very accurate position of the source as determined by this X-ray observation, a deep radio search for radio pulsations became feasible. The detection and study of any pulsed radio emission from this source would be interesting given the as-yet unclear connections between radio emission and X-ray activity in the classes of neutron stars described above, plus the physical insight to be gained from finding and studying another Be/X-ray binary radio pulsar.

2. OBSERVATIONS AND ANALYSIS

On 2008 February 1, we observed the source XTE J0103–728 continuously for 23,106 s (6.4 hr) with the Parkes 64 m telescope in Parkes, Australia. Data were taken with the center beam of the multibeam receiver (the most sensitive of the 13 receiver beams) at a center frequency of 1390 MHz. One reason this relatively high observing frequency was used is that PSR B1259–63, which is a possible comparison system, is known to be particularly weak at low frequencies (~ 400 MHz), possibly owing to an unusual spectral index (Johnston et al. 1994). A bandwidth of 256 MHz was used in our observation, split into 512 contiguous 0.5 MHz frequency channels. Dual linear polarizations were summed, and the frequency channels were one-bit sampled every 0.5 ms. This easily preserved the necessary sampling rate required to detect 6.85 s pulsations. The data were recorded on DLT tape and transferred from the observatory to a Beowulf cluster for processing. The SMC was previously surveyed for radio pulsars at this frequency (Manchester et al. 2006), but that survey used a shorter integration time, and XTE J0103–728 was not near the center of any of the survey beams. These factors made that survey less sensitive to radio pulses from XTE J0103–728 by about a factor of 3 compared to the search reported here.

The data from the Parkes observation were first checked for the presence of radio frequency interference (RFI). Interference signals above the 4σ threshold level were excised from the data, which removed $\sim 8\%$ of the time bins and frequency channels in the raw data prior to analysis. The data were then searched in several ways to look for radio pulsations, as described below.

2.1. Folding Search

In the first analysis, the data were split into sixteen 16 MHz subbands, and each subband was dedispersed at an assumed dispersion measure (DM) of 100 pc cm^{-3} . This is within the range of expected DMs for pulsars in the SMC (Manchester et al. 2006). A range of DMs was tried by shifting the subbands with respect to each other in phase, then summing the subbands in each case. DMs from 0 to 5000

pc cm^{-3} were searched in this way. A barycentric folding period was determined using the measured periods from the two previous X-ray detections of XTE J0103–728. Using the reported periods and their associated uncertainties from the 2003 May (Corbet et al. 2003) and 2006 October (Haberl & Pietsch 2008) observations, we extrapolated the period to the 2008 February epoch and determined the barycentric folding period to be $6.8563(3)$ s. Since the spin period of XTE J0103–728 is so large, a dedispersion error would not significantly degrade the sensitivity of our search. A dedispersion error of 100 pc cm^{-3} , for instance, would lead to only a 5 ms smear in the pulse across each subband, less than 0.1% of the pulse period. Even for the extreme case of a dispersion error of 5000 pc cm^{-3} , pulsations would probably still be detectable since the corresponding pulse smear would only be 3.6% of the pulse period.

Periods ± 40 ms from the nominal period were searched, which easily encompassed the estimated 0.3 ms uncertainty in the pulse period. In a separate analysis, the data were split into 10 segments, with each segment starting at intervals of 10% of the data length and consisting of 20% of the data length. Each segment was separately searched for variable strength pulsations (owing to scintillation, for example) in the manner described above. No candidate signals were detected in any of these analyses.

We also conducted a more detailed separate search in which we dedispersed and folded the data into pulse profiles at a range of DMs and folding periods around the nominal period. Periods spanning ± 1.5 ms from the nominal 6856.3 ms pulse period (i.e., a range of $\pm 5\sigma$) were searched in steps of $1 \mu\text{s}$. Each of these folding trials was conducted for DMs between 0 and 800 pc cm^{-3} in steps of 5 pc cm^{-3} . For each DM trial, the full 256 MHz of bandwidth was dedispersed. A total of 480,000 period and DM combinations were tried (3000 folds per DM trial, and 160 DM trials), and for each trial the χ^2 significance of the folded profile was recorded. For this number of random trials, we would expect a $\sim 25\%$ likelihood of producing at least one signal at the 5σ significance level or higher from noise alone. We therefore chose 5σ as a reasonable threshold to apply, and we found no folded profiles at the 5σ significance level or higher in the search.

This second search was more sensitive to pulsations having very small duty cycles, and we estimate the effects on the pulse width that either folding the raw data at a period that is offset from the true period or dedispersing the data at a DM that is offset from the true DM would have. We compare this amount of pulse smearing to the smearing already present in the finite frequency channels. Significant smearing of the pulse would greatly reduce the sensitivity of the search, so it is therefore important to ensure that the search parameters do not allow this. For the chosen period step size of 10^{-6} s in the search, the maximum folding period offset is 5×10^{-7} s from the true period. Folding the raw data at this offset period would cause a pulse smear across the folded profile of 1.7 ms (2.5×10^{-4} cycles) over the length of the observation. This is an order of magnitude larger than the intrachannel dispersive smearing of 0.16 ms (2.3×10^{-5} cycles) for an assumed DM $\sim 100 \text{ pc cm}^{-3}$, but it is still negligible for any reasonable duty cycle expected for the pulsar. The DM step size of 5 pc cm^{-3} produces a maximum DM offset from the true DM of 2.5 pc cm^{-3} , which for 256 MHz of bandwidth at our observing frequency yields a maximum dispersive smearing of 2.0 ms (2.9×10^{-4} cycles). Thus, any duty cycle $\gtrsim 10^{-3}$ should not be significantly affected by any of these smearing effects. The grid spacing of the period

⁶ The figure in parentheses represents the uncertainty in the last digit quoted.

and DM search ensured that no pulsations with very small duty cycles (narrow pulses) would have been missed in the search.

2.2. Periodicity Search

We also conducted a periodicity search of the data, which included a fast folding algorithm (FFA) search in addition to the more common Fourier search. A Fourier search is particularly important if the estimated spin period at the epoch of observation was not correct (e.g., if there were irregularities in the spin-down behavior or significant accelerations from binary motion that are not accounted for in the predicted folding period). For the Fourier search, two different packages were used: SIGPROC⁷ (e.g., Lorimer et al. 2000) and PRESTO⁸ (Ransom 2001; Ransom et al. 2002). A total of 828 DM trials ranging from 0 to 800 pc cm⁻³ were used in the search. The DM trials were spaced so that there would be no significant pulse smearing introduced beyond the smearing already present in the 0.5 MHz frequency channels. Each dedispersed time series was filtered, and a 2²⁵ point fast Fourier transform was performed.⁹ Each resulting spectrum was harmonically summed using 16 harmonics and searched for candidate periodicities. For the PRESTO search, an acceleration search spanning ± 100 Fourier bins was also performed on each dedispersed time series. This maintained full sensitivity to accelerations of up to 24 m s⁻² for the 6.856 s fundamental and 16 of its harmonics. No acceleration search was performed in the SIGPROC analysis. Candidates recorded in the frequency spectrum were further checked by dedispersing and folding the raw data at DMs and periods near the candidate values in the manner described in the folding search above. No promising candidates were detected in this search.

During the Fourier search, each dedispersed time series was also searched for significant periodicities using the FFA (Staelin 1969). We used publicly available FFA search code,¹⁰ described in detail by Kondratiev et al. (2009), which has been previously used to search for pulsed radio emission from XDINs. No signals were detected in the FFA periodograms above a signal-to-noise threshold of 5 for periods between 2 and 12 s.

2.3. Single Pulse Search

The recent discovery of bursting radio sources subsequently identified as rotating neutron stars (RRATs; McLaughlin et al. 2006) suggests that looking for dispersed single pulses is a powerful method by which to detect rotating neutron stars that would otherwise not be detectable in a periodic search. Besides RRATs, other classes of persistent and transient radio sources are sometimes detectable through their single pulses. For example, the AXP XTE J1810–197 exhibited very bright single pulses at the time of its radio detection (Camilo et al. 2006), and single pulse searches have been used to detect radio emission from a number of pulsars, including the Crab pulsar (Staelin & Reifenstein 1968). Dispersed, extremely luminous radio bursts from cosmological sources may also be present in the data and would only be detectable through this kind of search (Lorimer et al. 2007).

We searched for dispersed single pulses in the data using the same set of DMs used for the Fourier search described above (828 DMs of variable spacing from 0 to 800 pc cm⁻³).

The single pulse analysis procedure is outlined by Cordes & McLaughlin (2003) and uses a matched filtering approach to detect impulses of different widths in each dedispersed time series. A range of boxcar filter widths is used to maximize sensitivity on different timescales. Pulse widths between 0.5 and 1024 ms were searched by increasing factors of 2 for the boxcar filter width, and the detection threshold was determined for each filtering window by the level of RFI present. For pulse widths $\gtrsim 1$ s, the high-pass filter present in the observing system would significantly attenuate the impulse amplitude (see discussion below), so windows greater than ~ 1 s were not searched. Owing to the increased RFI presence as the window size increased, the signal-to-noise (S/N) detection threshold changed from 8 to 20 for boxcar windows greater than or equal to 4 ms. No significant dispersed single pulses were detected in this search.

2.4. Limits on Radio Emission

We used the modified radiometer equation (Dewey et al. 1985) to estimate the flux density limit on periodic emission in the folding search. For a detection S/N threshold of 5, 1-bit sampling, a gain of 0.735 K Jy⁻¹ for the center beam of the multibeam receiver (Manchester et al. 2001), an assumed duty cycle of 5%, and the observing parameters outlined above, we estimate the 1400 MHz flux density limit on pulsed emission from XTE J0103–728 to be ~ 13 μ Jy. This estimate does not include the effect of RFI, which can quite significantly degrade the sensitivity, especially at long periods. The corresponding 1400 MHz luminosity limit can be calculated using $L = Sd^2$, where S is the 1400 MHz flux density limit and d is the distance. In this definition, no geometrical factor for the beaming is included which would change the calculated luminosity limit. Using a distance of 60 kpc to the SMC (Hilditch et al. 2005), we estimate the 1400 MHz luminosity limit to be ~ 45 mJy kpc² (see Table 1). The sensitivity limit from the FFA search is comparable to the radiometer limit for the periodic emission.

Table 1
1400 MHz Radio Limits for XTE J0103–728

Parameter	Value
Observation date	2008 Feb 1
Observation MJD	54,497
1400 MHz flux density limit (periodic emission) ^a	13 μ Jy
1400 MHz luminosity limit (periodic emission) ^b	45 mJy kpc ²
1400 MHz flux density limit (single pulses) ^c	0.60–0.03 Jy
1400 MHz luminosity limit (single pulses) ^b	2150–120 Jy kpc ²

Notes.

^a Limit on periodic emission obtained from the modified radiometer equation assuming a 5% pulsed duty cycle and no degradation in sensitivity from RFI. The limit obtained from the blind Fourier search is roughly a factor of 2 higher (less sensitive) owing to the different detection algorithms used. The limits become significantly higher (less sensitive) than those calculated with the modified radiometer equation if a large duty cycle is assumed ($\gtrsim 20\%$ – 30%). This is due to the high-pass filtering present in the observing system which reduces sensitivity to pulse widths $\gtrsim 1$ s.

^b Luminosity limit obtained assuming a distance of ~ 60 kpc, the distance to the SMC (Hilditch et al. 2005).

^c Limits on single pulse emission for boxcar filter widths ranging from 0.5 ms to 1024 ms. The limits were obtained using the radiometer equation with an integration time equal to the window width and a detection S/N threshold that changed from 8 to 20 for filter widths greater than or equal to 4 ms. This change in detection threshold was chosen to account for the increased presence of RFI in the larger filter windows.

⁷ <http://sigproc.sourceforge.net>.

⁸ <http://www.cv.nrao.edu/~sransom/presto>.

⁹ For the PRESTO search, each dedispersed time series was padded out to 2²⁶ points so that all of the data would be used.

¹⁰ <http://astro.wvu.edu/projects/xdins>.

For the single pulse search, no pulses were detected down to the flux density limit of 0.60–0.03 Jy (depending on the S/N threshold and window size used in the filtering; see the discussion above). These limits correspond to 1400 MHz luminosity limits of 2150–120 Jy kpc² (Table 1) using a distance of 60 kpc to the SMC and the same luminosity definition.

The limits obtained by the modified radiometer equation are accurate representations of the sensitivity of the folding search (see Dewey et al. 1985; Lorimer et al. 2006). However, for the sample of pulsars that were detected in the Parkes Multibeam Survey (Manchester et al. 2001), the S/N values of the Fourier detections from the blind Fourier search are lower than the corresponding folded profile S/N values by about a factor of 2 (on average) near the detection threshold (F. Crawford et al. 2009, in preparation). This difference would apply here also since the same observing system and a similar analysis procedure were used. We therefore estimate the baseline sensitivity limit for the Fourier search to be $\sim 25 \mu\text{Jy}$, roughly twice the modified radiometer equation limit. Since we had a good estimate of the folding period for this search, we elect to keep the radiometer limit as an accurate estimate of the sensitivity to periodic emission for our discussion.

Another factor which must be considered in the estimate of the sensitivity to pulsed emission (either impulsive or periodic) is the presence of a high-pass filter in the observing system which severely limits the sensitivity to long-period pulsars having large duty cycles. This high-pass filter is modeled as a two-pole filter with a time constant of 0.9 s (Manchester et al. 2001), and the effect of this filter on long-period signals depends on the duty cycle of the pulse as it is received at the telescope (i.e., after interstellar dispersive and scattering effects have already affected the pulse width and shape). In order to quantify this filtering effect on the sensitivity, we created synthetic pulse trains in software with various periods and duty cycles and passed these signals through a two-pole high-pass filter (in software) in order to gauge the amount of signal attenuation and hence reduction in the detected S/N. We found that for duty cycles greater than $\sim 20\%$ – 30% , the attenuation is significant for a ~ 6 s pulsar (there is a reduction of $\gtrsim 10\%$ in the pulse amplitude). For duty cycles less than $\sim 10\%$, the effect is negligible; this is due to the presence of a larger number of high-frequency harmonics of the fundamental in the signal that are not as significantly affected by the high-pass filtering. These results are consistent with the simple expectation that pulse widths greater than the 0.9 s filtering time constant would be significantly attenuated. This filtering effect also has relevance for the flux density upper limits recently reported for several radio search observations of AXPs conducted with Parkes. Both Burgay et al. (2006b) and Crawford et al. (2007) searched four AXPs with periods of 6 and 11 s with the multibeam observing system. For small assumed duty cycles (less than 10%), the attenuation is negligible for these periods. For our single pulse search of XTE J0103–728, impulsive signals having widths $\gtrsim 1$ s are attenuated by the filter, which is why our single pulse search window range did not extend beyond 1024 ms.

3. DISCUSSION

Our 1400 MHz luminosity upper limit for the periodic radio emission from XTE J0103–728 is estimated to be ~ 45 mJy kpc² (Table 1). Below we compare this limit to the luminosities of neutron star systems having characteristics similar to XTE J0103–728. In particular, we compare our result to PSR

B1259–63, the one known radio pulsar in a Be/X-ray binary system, and to neutron stars having long spin periods.

3.1. Comparison with PSR B1259–63

There are three binary radio pulsars known to have nondegenerate orbital companions: PSRs J0045–7319 (Kaspi et al. 1994), J1740–3052 (Stairs et al. 2001), and B1259–63 (Johnston et al. 1992). Of these three, only PSR B1259–63 orbits a Be star. There are also many Be/X-ray HMXBs that are known, including more than 60 in the SMC (Haberl & Pietsch 2008), but apart from PSR B1259–63, none of these has yet been observed as a radio pulsar. For this reason, PSR B1259–63 is a natural system with which to compare our results for XTE J0103–728.

PSR B1259–63 is in a highly eccentric and wide orbit, with an eccentricity of 0.87 and an orbital period of 3.4 years (Johnston et al. 1994). The pulsar passes quite close to its Be star companion at periastron, coming within 24 stellar radii of the star (Johnston et al. 2005). This distance is comparable to the estimated radius of the circumstellar disk of the Be star, which is thought to be at least 20 stellar radii in size (Johnston et al. 1994). Near periastron, the radio pulses from PSR B1259–63 are eclipsed for ~ 40 days by the circumstellar disk. Enhanced X-ray emission is also detected near periastron, since the pulsar interacts with the stellar wind (Kaspi et al. 1995). However, pulsed X-rays have not been detected from PSR B1259–63, unlike XTE J0103–728. Melatos et al. (1995) modeled the B1259–63 system near periastron and investigated two models which could explain the observed eclipsing behavior. They found that a model employing a cool, dense equatorial disk around the Be star successfully predicted the observed eclipse duration at ~ 1.5 GHz, if free–free absorption were the primary eclipsing mechanism. They also found that scattering in the disk may be contributing to the radio eclipse. In any case, it seems reasonable that free–free absorption and scattering could also be preventing the detection of radio pulses from XTE J0103–728 if it is in a similarly eccentric orbit and was near periastron at the time of our observation.

The 1400 MHz flux density of pulsed emission from PSR B1259–63 has been measured and published in a variety of papers using data collected over the course of several orbits (Hobbs et al. 2004; Johnston et al. 1992, 1994, 1996, 2005; Connors et al. 2002). The measured values vary considerably, but consideration of all the measurements suggests an average flux density of ~ 5 mJy around 1400 MHz. We use this estimate for the comparison with our observation of XTE J0103–728. Near periastron, when PSR B1259–63 is eclipsed, there is no detectable radio emission at this frequency. We adopt ~ 1 mJy as a conservative upper limit on the flux density during eclipse by considering the uncertainties in the 1400 MHz flux reported both before and after the eclipse during the 2000 and 2004 periastron passages (Connors et al. 2002; Johnston et al. 2005). The best estimate for the distance to PSR B1259–63 is 1.5 kpc, based on optical observations of the Be star companion (Johnston et al. 1994). From this, the resulting 1400 MHz luminosities are calculated to be ~ 11 mJy kpc² away from periastron and $\lesssim 2$ mJy kpc² during eclipse near periastron. In either case, the luminosity is below the limit of ~ 45 mJy kpc² that we have established for pulsed emission from XTE J0103–728 at the epoch of our observation. We therefore cannot rule out radio emission from XTE J0103–728 that is comparable in luminosity to the emission seen from PSR B1259–63.

3.2. Comparison with Other Long-Period Neutron Stars

In this section, we compare the luminosity upper limit for XTE J0103–728 to the radio luminosities (or luminosity upper limits in some cases) of neutron stars which have long spin periods like XTE J0103–728.

In the ATNF pulsar catalog (Manchester et al. 2005), there are five radio pulsars with periods greater than 6 s that have measured 1400 MHz flux densities and corresponding estimated luminosities. The radio luminosities of these pulsars range from 0.03 to 23 mJy kpc², which is below our upper limit of ~45 mJy kpc² for periodic emission from XTE J0103–728. The sample of six long-period XDINs for which new, sensitive radio limits have recently been obtained using the Green Bank Telescope (Kondratiev et al. 2009) has 1400 MHz luminosity limits that are several orders of magnitude below our limit. These XDINs have periods ranging from 7 to 11 s. There are five AXPs with periods longer than 6 s which have been searched at 1400 MHz for radio emission and for which luminosity upper limits have been established (Burgay et al. 2006b; Crawford et al. 2007; Burgay et al. 2006a). Although these AXPs are believed to have much stronger magnetic fields than the neutron stars in these other classes, they may have similar beaming and detectability selection effects in the radio owing to their similarly long spin periods (see discussion below). The luminosity limits established for these AXPs are all around 1 mJy kpc², which is more than an order of magnitude below our limit for XTE J0103–728. A radio search was also previously conducted on SGR 0526–66 in the Large Magellanic Cloud, which, like the AXPs, is also believed to be a magnetar. No radio emission was detected from SGR 0526–66 down to an upper limit of ~350 mJy kpc² at 1400 MHz (Crawford et al. 2002).

By looking at these values, one can see that it is entirely possible that XTE J0103–728 could have radio emission comparable in strength to these long-period radio pulsars, XDINs, and AXPs (if these latter two classes are in fact radio emitters), and that we are simply not detecting radio pulsations due to a lack of sensitivity. Unfortunately, the large distance to XTE J0103–728 makes the limit impossible to significantly improve upon until next-generation instruments, such as the Australia Square Kilometer Array Pathfinder (ASKAP; Johnston et al. 2007, 2008), can be developed and used. Even if XTE J0103–728 were a strong radio emitter, its radio beam might not be aligned with its X-ray beam and could miss our line of sight. If this were the case, XTE J0103–728 might remain undetectable to us in the radio owing to its emission geometry.

Narrow pulse widths are also generally observed for long-period radio pulsars. For instance, the two cataloged radio pulsars with the longest spin periods, PSRs J2144–3933 and J1001–5939, have full width at half-maximum radio pulse widths of 0.2% and 0.5% of the pulse period, respectively (Young et al. 1999; Lorimer et al. 2006). These duty cycles are among the smallest measured for the radio pulsar population and indicate the severity of the selection effects that might be preventing the detection of many long-period radio pulsars, of which XTE J0103–728 might be one. Note that the small duty cycle associated with the narrow pulses would partially compensate for the sensitivity selection effect on long-period pulsars from the high-pass filtering (described above), since there would be many high-frequency harmonics in the signal.

4. CONCLUSIONS

The X-ray pulsations from XTE J0103–728 that were first detected by Corbet et al. (2003) with RXTE were detectable over the course of a few weeks. This suggests that the source underwent a Type II outburst, caused by the expansion of the circumstellar disk around the Be star, with subsequent enhanced accretion onto the neutron star surface (Haberl et al. 2008; Haberl & Pietsch 2008). If, however, the X-ray emission detected in 2006 was from a Type I burst, which lasts for a few days during periastron passage and recurs periodically with the orbital period of the system (e.g., Okazaki & Negueruela 2001), then our radio observation likely occurred well away from periastron, assuming that the orbit of XTE J0103–728 is sufficiently wide and eccentric, as is the case for most Be/X-ray binaries (Liu et al. 2000). In this case, radio pulses from XTE J0103–728 may be more likely to be seen, since radio pulses from PSR B1259–63 are detectable for the majority of its 3.4 years orbit.

This also points to the value of repeated radio search observations of Be/X-ray binaries such as XTE J0103–728, since their emission properties can vary significantly at different orbital phases. Future radio search observations of XTE J0103–728 would be valuable, especially if observations can be conducted that could sample the orbital phase of the system well. It may also be the case that XTE J0103–728 emits only very weak radio emission (or perhaps no radio emission at all), that the radio and X-ray beams are not aligned with each other, or that a strong but narrow radio beam misses our line of sight, making this source undetectable in the radio.

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