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NO DETECTABLE RADIO EMISSION FROM THE MAGNETAR-LIKE PULSAR IN Kes 75

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ABSTRACT

The rotation-powered pulsar PSR J1846−0258 in the supernova remnant Kes 75 was recently shown to have exhibited magnetar-like X-ray bursts in mid-2006. Radio emission has not yet been observed from this source, but other magnetar-like sources have exhibited transient radio emission following X-ray bursts. We report on a deep 1.9 GHz radio observation of PSR J1846−0258 with the 100 m Green Bank Telescope in late 2007, designed to search for radio pulsations or bursts from this target. We have also analyzed three shorter serendipitous 1.4 GHz radio observations of the source taken with the 64 m Parkes telescope during the 2006 bursting period. We detected no radio emission from PSR J1846−0258 in either the Green Bank or Parkes data sets. We place an upper limit of 4.9 μJy on coherent pulsed emission from PSR J1846−0258 based on the 2007 November 2 observation, and an upper limit of 27 μJy around the time of the X-ray bursts. Serendipitously, we observed radio pulses from the nearby RRAT J1846−02, and place a 3 σ confidence level upper limit on its period derivative of 1.7×10^{-13}, implying its surface dipole magnetic field is less than 2.6×10^{13} G.

Subject headings: pulsars: individual (PSR J1846−0258, RRAT J1846−02)

1. INTRODUCTION

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are now well accepted as being different although similar manifestations of "magnetars": isolated, young ultrahighly magnetized neutron stars whose radiation is powered by their magnetic field (see Woods & Thompson 2006 for a review). However, there remain some outstanding puzzles in the magnetar picture. One is the connection between magnetars and high-magnetic-field rotation-powered pulsars. There are now seven known otherwise ordinary rotation-powered pulsars having inferred surface dipole magnetic field $B > 4 \times 10^{13}$ G [computed using the standard formula $B = 3.2 \times 10^{19}$ G $(P\dot{P})^{1/2}$; the quantum critical field $B_{\rm QED} = 4.4 \times 10^{13}$ G]. Most of these high-magnetic-field pulsars, for example PSRs J1718−3718, J1847−0130, and J1814−1744, have B similar to or greater than those measured for bona fide magnetars, yet show only faint X-ray emission, if any (McLaughlin et al. 2003; Kaspi & McLaughlin 2005; Pivovaroff et al. 2000). The rotating radio transient (RRAT) J1819−1458 also has a field comparable to magnetars, but it exhibits modest X-ray emission (McLaughlin et al. 2007). Gonzalez et al. (2005) suggest that another high-B radio pulsar, PSR J1119−6127, shows evidence for possibly anomalous X-ray emission in the form of a high surface temperature and high pulsed fraction for thermal emission.

"Transient" magnetars, such as XTE J1810−197, are typically X-ray faint but occasionally have major AXP-like outbursts (e.g., Ibrahim et al. 2004). Similarly, the candidate transient AXP AX J1845−0258 is either extremely faint or undetectable in quiescence, but was seen to be at least several hundred times brighter than usual in a 1993 outburst (Vasisht et al. 2000; Tam et al. 2007). Kaspi & McLaughlin (2005) suggest that such objects could be related to high-B radio pulsars, noting the similarity of the spectrum of the high-B radio pulsar PSR J1718−3718 to that of XTE J1810−197 in quiescence. This suggestion was supported by the discovery of radio pulsations from XTE J1810−197 after its major outburst (Camilo et al. 2006), albeit with an unusual radio spectrum and unusual radio variability properties. Camilo et al. (2007a) report a second magnetar, 1E 1547.0−5408, in outburst with similar radio properties.

Very recently, the proposed connection between high-B radio pulsars and magnetars was given a major boost by the discovery of SGR-like X-ray bursts and a several-month-long flux enhancement from PSR J1846−0258, which was previously thought to be a purely rotation-powered pulsar (Gavriil et al. 2008). This source has a quiescent X-ray luminosity that could be rotation-powered, and has other properties of rotation-powered pulsars, such as a pulsar wind nebula (PWN; Helfand et al. 2003; Kumar & Safi-Harb 2008; Ng et al. 2008) and an unremarkable braking index of 2.65 ± 0.01 (Livingstone et al. 2006). PSR J1846−0258 has a period of 326 ms, an estimated dipole magnetic field of 4.9×10^{13} G , and an estimated spin-down age of 884 yr (Livingstone et al. 2006). Its accurate position, obtained with the *Chandra* observatory, clearly associates it with the supernova remnant (SNR) Kes 75 (Helfand et al. 2003). However, no radio emission has yet been detected from the pulsar (Kaspi et al. 1996).

Here we report on radio observations of PSR J1846−0258, obtained fortuitously on the same day as the onset of its observed magnetar-like X-ray behavior, as well as over a year after this episode. Using these data, we have searched for coherent radio pulsations. We also report on our search for single radio bursts from this source. We find neither radio pulsations nor bursts, and set upper limits on both. However, we do detect and describe radio bursts from a nearby, unrelated RRAT J1846−02 (McLaughlin et al. 2006).

2. OBSERVATIONS AND RESULTS

We obtained a deep observation of PSR J1846−0258 with the 100 m Robert C. Byrd telescope at Green Bank, West Virginia, operated by the NRAO.[3] The RRAT J1846−02 (McLaughlin et al. 2006) is estimated to be within 2′ of PSR J1846−0258, although its position is uncertain by ∼7′. Since the well-known periods of

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RRAT J1846−02 (4.4767 s) and PSR J1846−0258 (326.29 ms) are incommensurable (their ratio is 13.720), they are clearly distinct sources. We were also able to analyze several archival observations, taken with the 64 m Parkes radio telescope in New South Wales, Australia, covering the key period during and just after the X-ray bursts described by Gavriil et al. (2008). Together these observations constrain radio emission associated with the X-ray bursts on both long and short timescales.

There are two distance estimates in the literature for PSR J1846−0258, 21 kpc (Becker & Helfand 1984) and 5–7.5 kpc (Leahy & Tian 2008). Using the NE2001 free electron density model (Cordes & Lazio 2002), these distances predict a range of dispersion measures (DMs) from 210 to 1441 pc cm^{-3}; the DM through the entire Galaxy in this direction is estimated to be 1464 pc cm^{-3}, although these figures are quite uncertain. The interstellar scattering times predicted by the NE2001 model range from 0.03 to 17 ms for a 1.9 GHz observing frequency, and from 0.1 to 65 ms for a 1.4 GHz observing frequency.

The intrinsic radio pulse width of PSR J1846−0258 is uncertain; the X-ray pulse is quite broad (Gotthelf et al. 2000), but X-ray pulse morphology can be very different from radio pulse morphology (e.g., as described in Gotthelf & Halpern [2005] and Camilo et al. [2007d], XTE J1810−197 had a broad X-ray profile but a small radio duty cycle). For the (mostly radio) pulsars listed in Manchester et al. (2005), the average duty cycle was about 5%, and the transient AXP XTE J1810−197 was observed with a variable duty cycle with typical value of 2% (Camilo et al. 2007d). Single pulses from the RRATs had lengths from 2 to 30 ms (McLaughlin et al. 2006). We elected to focus our search on a duty cycle of about 1%, that is, pulses of length 3 ms. We ran folding and single-pulse searches (see below) that were sensitive to somewhat shorter pulses, but pulses shorter than the time resolution of our searches would be detected (or not) according to their flux averaged over our time resolution; if the pulse length is $\alpha < 1$ times our search's time resolution, our sensitivity to the peak flux is reduced by a factor of $\sqrt{\alpha}$. Our tools are generally fairly sensitive to pulses longer than the time resolution, so we have tried to choose parameters that allow us to detect a broad range of duty cycles around 1%.

2.1. *Deep Single Observation with the Green Bank Telescope*

We observed PSR J1846−0258 while pointing at R.A. $18^{\rm h}46^{\rm m}24.96^{\rm s}$, decl. $-2°58'30.72''$ (J2000; Helfand et al. 2003) for 201 minutes, beginning at MJD 54406.969 (2007 November 2, 23 : 14 UTC), using the Green Bank Telescope. We used the S-band receiver, observing a bandwidth of 600 MHz centered at 1950 MHz, feeding into the SPIGOT pulsar back end (Kaplan et al. 2005), which recorded 1024 channels (only 768 of which were within our bandpass) of 16 bit samples with a time resolution of 81.92 μs. The two linear polarization channels were summed. We performed RFI excision using the program `rfifind` from the software package PRESTO (Ransom 2001; Ransom et al. 2002). RFI conditions were mild, requiring only ∼4% of the data to be discarded.

We analyzed the data in three ways: by trial folding, by using a Fourier-domain blind periodicity search, and by searching for bright dispersed single pulses.

Trial folding was carried out using the program `prepfold` from PRESTO. We folded the data into 64 pulse phase bins at 1281 evenly spaced DMs ranging from 0 to 4288 pc cm^{-3}. These DM spacings correspond to a shift of a single profile bin over the whole observation time per step. In case the pulsar has a very large or very small duty cycle, we also repeated the search with 16 and 256 phase bins, with corresponding numbers of DM trials and the same minimum and maximum DM. The ephemeris we used for folding was taken from contemporaneous *Rossi X-ray Timing Explorer* (*RXTE*) observations, part of the program described in Livingstone et al. (2006). The timing model we used specifies the pulsar's rotational frequency as

$$\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \ddot{\nu}_0(t - t_0)^2/2, \quad (1)$$

where $\nu_0 = 3.064756108(4)$ Hz, $\dot{\nu}_0 = -6.6888(4)\times10^{-11}$ Hz s^{-1}, $\ddot{\nu}_0 = 4.81(12)\times10^{-20}$ Hz s^{-2}, and t_0 is MJD 54376.452350. Period and period derivative uncertainties obtained from this ephemeris are insignificant over the course of this observation.

We detected no radio pulsations at or near the trial ephemeris. The GBT observing guide describes a system temperature $T_{\rm sys}$ of approximately 19.5 K for this band and a gain G of approximately 1.75 K Jy^{-1}. Since the band at which we observed, 2 GHz, is more or less free of both ionospheric and tropospheric effects and the GBT receivers are quite stable, this number should be reasonably accurate. We modeled the background $T_{\rm BG}$ as a continuum of 400 K at 408 MHz (Haslam et al. 1982), which we assumed to have a spectral index of −2.6, plus a contribution $S_{\rm SNR}$ from the supernova remnant of 10 Jy at 1.4 GHz with a spectral index of −0.7 (Green 2006). To compute the upper limit on the pulsar's mean flux, $S_{\rm min}$, we use the expression (e.g., Lorimer & Kramer 2005)

$$S_{\rm min} = ({\rm S/N})_{\rm min}\beta\sqrt{\frac{W}{P - W}}\,\sigma, \quad (2)$$

where $({\rm S/N})_{\rm min}$ is the signal-to-noise threshold at which we would certainly have detected the pulsations, β is a unitless factor describing quantization losses, P is the pulsar's period, W is the time per period during which the pulsar is on, and σ is the noise rms amplitude, given by

$$\sigma = \frac{(T_{\rm sys} + T_{\rm BG})/G + S_{\rm SNR}}{\sqrt{n_p t \Delta f}}, \quad (3)$$

where n_p is the number of polarizations added (2 in our case), t is the observation length (201 minutes), and Δf is the bandwidth (600 MHz). Since the Spigot uses a three-level digitzer, we used $\beta = 1.16$ (Lorimer & Kramer 2005). For this calculation, we assumed that the duty cycle was 1/64, and that we would have detected any pulsar with a peak more than 4 times the rms noise per bin. This gives an upper limit of 4.9 μJy. Longer duty cycles give higher upper limits, up to 43 μJy (assuming a square-wave profile).

We carried out the blind periodicity search using the program `accelsearch`, again from the PRESTO toolkit. We produced a dedispersed time series with time resolution 0.32768 ms for 2000 dispersion measures spaced by 2 pc cm^{-3} from 0 to 4000 pc cm^{-3}. We searched only for unaccelerated pulsations, summing up to 16 harmonics (the maximum supported by `accelsearch`). We detected no pulsations. We examined all candidates with a signal-to-noise ratio above 6. Applying equations (2) and (3) as we did for our coherent pulsation search, and assuming a duty cycle of 1/32 (since the use of 16 harmonics smears the folded profile by this much), we place an upper limit on coherent pulsations at any frequency of 10 μJy.

We carried out the single-pulse search using `single_pulse_search.py`, again from the PRESTO toolkit. This software operates on the same dedispersed time series described above, and computes running boxcar averages at a range of widths from our dedispersed sample time of 0.32768 ms up to 9.8304 ms.

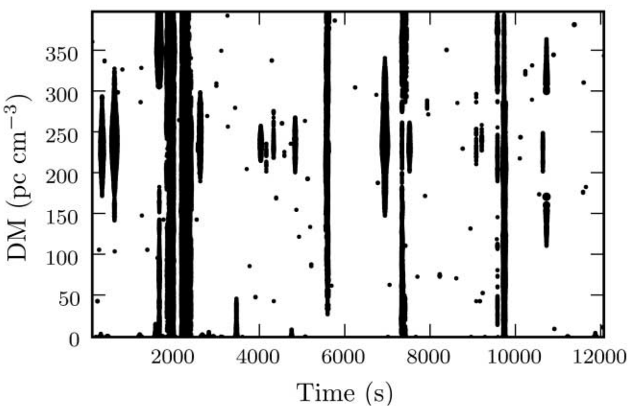

FIG. 1.— Single-pulse search results plot from our 3 hr Green Bank Telescope observation. Each single pulse detection above a threshold of 6 σ is plotted as a circle whose diameter indicates the significance of the detection. Note the series of pulses from the RRAT J1846−02 around a DM of 237 pc cm^{-3}. The final, brightest, pulse from the RRAT, just before 11000 s, appears only below a DM of 170 pc cm−3 and above DM 300 pc cm^{-3} because it was so strong it was erroneously identified as a receiver gain change in dedispersed time series closer to the correct DM. Vertical groups of strong detections extending down to zero DM are RFI.

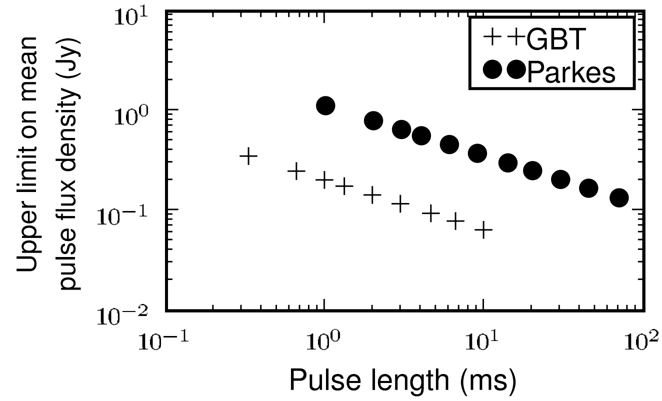

FIG. 2.—Upper limits on the mean flux density for single pulses of different lengths for our GBT (§ 2.1) and Parkes (§ 2.2) observations.

Statistically significant detections are recorded (after some automated sifting to reduce the effects of radio frequency interference and receiver gain changes), and the results are plotted in Figure 1. The peak-flux threshold for detection of single pulses depends on the length of the pulses (see Fig. 2). The single-pulse searching code we used removes certain strong pulses which it interprets as receiver gain changes. As a result, the last and brightest pulse was erroneously removed from the list of single-pulse detections between a DM of 170 pc cm^{-3} and a DM of 300 pc cm^{-3}. It was nevertheless present in our dedispersed time series, and we used it in our timing analysis.

The signature of a single bright astrophysical pulse should be a collection of single-pulse detections well above the DM $=0$ axis. Indeed, we find a number of such pulses, at a DM of approximately 237 pc cm^{-3}. Closer examination reveals 12 bright single pulses, all clustered around this DM. A number of other pulse detections were observed, but all appear to be either terrestrial RFI (groups of detections at the same time and strongest at zero DM) or noise.

When we fold the arrival times of all single-pulse candidates (apart from certain obvious RFI) according to our ephemeris for the X-ray pulsar in Kes 75, we find that they fall at random phases; in fact a Kuiper test gives a probability of 0.22 that a uniform distribution would give rise to arrival times more unevenly distributed in phase than this. However, the RRAT J1846−02, described in McLaughlin et al. (2006), falls within the GBT's 7′ beam when it is pointed at PSR J1846−0258. The DM reported in McLaughlin et al. (2006) is 239 pc cm^{-3}, which closely matches that of our single pulses. Moreover, if we fold the single-pulse arrival times at the reported period of the RRAT, 4.476739(6) s, we find that they fall within 4 milliperiods of the same phase. We therefore infer that the only significant cosmic single pulses in our observation are from RRAT J1846−02.

Since we detected 12 bright pulses from the RRAT J1846−02 over the course of approximately 3 hr, we can compute a period for the RRAT based on the timing of single pulses. We selected the single brightest pulse, smoothed it by convolution with a von Mises distribution (e.g., Mardia 1975) of full width at half-maximum 10 ms, and used it as a template. The barycentric arrival time of each pulse was estimated by Fourier-domain cross-correlation with this template. We then used the published period to compute the number of turns between each pair of pulses, and adjusted the period and starting phase to minimize the root-mean-squared residual phase.

While we would expect rather small formal errors on the arrival times for data of this quality, we do observe about 4 ms residual jitter, possibly due to pulse shape variations. We have used the rms variation of the residuals as an estimate of the uncertainty on each arrival-time measurement. Taking this into account, we obtain a barycentric period estimate of 4.4767435(2) s at epoch MJD 54407. Subtracting this from the reported period of 4.476739(3) s (epoch MJD 53492; McLaughlin et al. 2006) and dividing by the elapsed time gives a period derivative estimate of $(5.5 \pm 3.8) \times 10^{-14}$, implying a 3 σ upper limit on the period derivative of 1.7×10^{-13}. Using $B = 3.2 \times 10^{19}$ G $(P\dot{P})^{1/2}$, this implies an upper limit on the surface dipole magnetic field of 2.6×10^{13} G.

2.2. *Observations with the Parkes Telescope Near the Bursting Epoch*

As part of a program to monitor RRAT J1846−02, three 1 hr observations including both it and PSR J1846−0258 were taken at MJDs 53886.64, 53923.54, and 53960.45. Bursts from PSR J1846−0258 were detected in X-ray observations at MJD 53886.92−53886.94 and 53943.46 (Gavriil et al. 2008); fortuitously, one radio observation was taken only 6 hr before the first of these bursts.

The radio observations were taken with a 256 MHz bandwidth centered at 1390 MHz. Each observation was 60 minutes long, and was recorded with the center beam of the Parkes Multibeam receiver. They were one-bit digitized with a time resolution of 0.1 ms and 512 spectral channels. We analyzed them in the same three ways as for the GBT data—folding at the known period, blind periodicity searching, and single-pulse searching—using the same software tools. Unfortunately, because of the timing anomaly that the source underwent around this time (Gavriil et al. 2008), we were not able to produce a phase-coherent timing solution from contemporaneous *RXTE* data. We were able to obtain period estimates from periodograms of the *RXTE* data, and we searched a range of periods in the radio data to be certain of including the true period.

We folded each observation using 64 phase bins at 129 periods centered at the peridogram frequency of the nearest *RXTE* observation and spaced over 1.4 μs, and 1025 DMs spaced from 0 to 4008 pc cm^{-3}. As before, we also folded with 16 and 256 bins. The center frequencies we used for this folding are 3.067684, 3.067457, and 3.067240 Hz, from *RXTE* observations at MJDs

53886.91, 53920.95, and 53955.57 for the Parkes observations on MJD 53886.64, 53923.54, and 53960.45, respectively. We saw no coherent pulsations. Using the same background figures and duty cycle assumptions as above, and telescope parameters obtained from the Parkes Radio Telescope Users' Guide (T_{sys} = 23.5 K, $G = 0.67$ K Jy^{-1}, $\beta = 1.25$), we estimate a flux upper limit of 27 μJy for each observation.

Our blind searches were carried out as above, and we set an upper limit of $\sim$58 μJy on all coherent pulsations from the source. For single-pulse search upper limits, see Figure 2. We detected single pulses from RRAT J1846$-$02 in one of these data sets. Only one pulse in our 3 hr GBT observation was brighter than our threshold for detection in the Parkes observations, so a single detection in the three 1 hr Parkes observations is not unexpected.

3. DISCUSSION

We did not detect radio emission from PSR J1846$-$0258, in spite of a deep GBT observation and a contemporaneous timing solution. Our upper limit of 4.9 μJy is a substantial improvement over that published in Kaspi et al. (1996), which quotes an upper limit at 1520 MHz of 100 μJy.

Two distance estimates for the pulsar/supernova remnant system are found in the literature: 21 kpc (Becker & Helfand 1984), and more recently 5.1–7.5 kpc (Leahy & Tian 2008). This newer result is based on more recent H I and ^{13}CO maps. The smaller distance yields a smaller diameter for the remnant, consistent with the indications that PSR J1846$-$0258 is very young (Livingstone et al. 2006). The smaller distance also yields a smaller X-ray luminosity for the pulsar, which had previously appeared to be unusually high (Helfand et al. 2003; 4.1×10^{35} erg s^{-1}, second only to the Crab). We will assume this more recent measurement is correct.

The transient AXP XTE J1810$-$197 was detected with 1.4 GHz radio flux densities peaking at 1500 mJy and fading to 10 mJy over the course of about 6 months (Camilo et al. 2007b), with a flat enough spectrum that flux densities at 1.4 and 1.9 GHz are comparable (Camilo et al. 2006). Its estimated distance is 3.5 kpc (Camilo et al. 2007b). If the source we observed had the same luminosity at the far end of the Leahy & Tian (2008) estimated distance range, 7.5 kpc, we would expect a flux density ranging from 320 mJy down to 2 mJy. The transient AXP 1E 1547.0$-$5408 was observed to have a flux density $\sim$3 mJy at 1.4 GHz (Camilo et al. 2007a), rising with frequency; the source is at an estimated distance of 9 kpc (Camilo et al. 2007a). If PSR J1846$-$0258 had the same luminosity, we would expect a flux of 4 mJy. All of these figures are significantly higher than our GBT detection threshold of 4.9 μJy, so we conclude that if PSR J1846$-$0258 was emitting radio pulsations during our observations, they must either be much weaker than those observed from transient magnetars, or they must be beamed elsewhere. A recent paper by Ng et al. (2008) computes an angle of 60° between the line of sight and the spin axis of the pulsar, and they combine this with a tentative suggestion that in order to obtain the observed braking index, the magnetic inclination should be approximately 9° (Melatos 1997; Livingstone et al. 2006). This would imply that our line of sight is, at its closest, 51° from the magnetic pole, making it unlikely that we would be in the pulsar beam. However, in light of the evidence given by Camilo et al. (2007c) that the X-ray and radio emission beams of XTE J1810$-$197 are nearly parallel, the fact that we see X-ray emission from PSR J1846$-$0258 indicates that if it behaved like XTE J1810$-$197, any radio emission would likely be beamed in our direction as well.

Thus, it appears likely that if PSR J1846$-$0258 is emitting radio pulsations, they are much weaker than those emitted by the known radio-emitting transient AXPs. However, since our GBT observation was taken some 18 months after the X-ray bursting activity, it is possible that the radio emission had faded by the time of our observation. The upper limits obtained from our Parkes observations (21 μJy) are also much less than we would have expected to observe from the known transient AXPs, so we can also constrain the brightness for the first 2 months after the X-ray bursts began. In particular, the X-ray bursts (four were observed in a 1 hr observation, taking place only 6 hr after the first of our Parkes observations) are probably not accompanied by radio bursts.

Leaving aside the AXP-like behavior of PSR J1846$-$0258, its radio emission appears to be very faint. The young pulsar PSR J0205+6449 in the supernova remnant 3C 58 is detected in X-rays and very faintly at radio wavelengths. It is at an estimated distance of 3.2 kpc. The radio flux at 1.4 GHz is 45 μJy, with a spectral index of -2.1 (Camilo et al. 2002). If PSR J1846$-$0258 had the same luminosity and spectral index, we would have received a flux of 4.3 μJy at 1.9 GHz, just comparable to our upper limit. On the other hand, the X-ray luminosity of PSR J0205+6449 is estimated to be 2.84×10^{33} erg s^{-1} (Murray et al. 2002), while the X-ray luminosity of PSR J1846$-$0258 is estimated to be 7×10^{34} erg s^{-1} (Morton et al. 2007 adjusted to the Leahy et al. distance estimate). Thus, in spite of having an X-ray luminosity more than 20 times that of PSR J0205+6449, PSR J1846$-$0258 appears to have a smaller radio luminosity than PSR J0205+6449. Beaming may account for this difference. More generally, the pseudoluminosity limit we set is 0.2 mJy kpc^2. Only 18 pulsars have been detected at radio wavelengths that are fainter than this limit; their luminosities range down to 30 μJy kpc^2 (Manchester et al. 2005).

It is possible that PSR J1846$-$0258 produced radio emission that peaked several months after the X-ray event and faded by the time of our GBT observation. XTE J1810$-$197 was observed to brighten in radio about a year after its X-ray brightening, and it faded over the course of about a year (Camilo et al. 2007c). We intend to search other observations from the monitoring program of RRAT J1846$-$02 for pulsations coming from PSR J1846$-$0258.

By comparing the period of RRAT J1846$-$02 measured from our observation with the published period, we were able to place a 3 σ upper limit on the spin-down rate of 1.7×10^{-13}. This gives a 3 σ upper limit on the surface dipole magnetic field of 2.6×10^{13} G, smaller than any known magnetar, and less than those of 24 more highly magnetized rotation-powered pulsars (Manchester et al. 2005), including PSR J1846$-$0258. We hope to combine this relatively long observation with a timing program being carried out by McLaughlin et al. to yield a phase-coherent timing solution for the RRAT J1846$-$02.

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Facilities: GBT (S-band receiver), Parkes (multibeam receiver)

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