1E 1547.0−5408: A RADIO-EMITTING MAGNETAR WITH A ROTATION PERIOD OF 2 SECONDS

F. CAMILO, S. M. RANSOM, J. P. HALPERN, AND J. REYNOLDS

Received 2007 June 29; accepted 2007 July 24; published 2007 August 24

ABSTRACT

The variable X-ray source 1E 1547.0−5408 was identified by Gelfand & Gaensler as a likely magnetar in G327.24−0.13, an apparent supernova remnant. No X-ray pulsations have been detected from it. Using the Parkes radio telescope, we discovered pulsations with period \( P = 2.069 \) s. Using the Australia Telescope Compact Array, we localized these to 1E 1547.0−5408. We measure \( P = (2.318 \pm 0.005) \times 10^{-11} \), which for a magnetic dipole rotating in vacuo gives a surface field strength of \( 2.2 \times 10^{14} \) G, a characteristic age of 1.4 kyr; and a spin-down luminosity of \( 1.0 \times 10^{35} \) erg s\(^{-1}\). Together with its X-ray characteristics, these rotational parameters of 1E 1547.0−5408 prove that it is a magnetar, only the second known to emit radio waves. The distance is \( \approx 9 \) kpc, derived from the dispersion measure of 830 cm\(^{-3}\) pc. The pulse profile at a frequency of 1.4 GHz is extremely broad and asymmetric due to multipath propagation in the ISM, as a result of which only \( \approx 75\% \) of the total flux at 1.4 GHz is pulsed. At higher frequencies the profile is more symmetric and has FWHM = 0.12\( P \). Unlike in normal radio pulsars, but in common with the other known radio-emitting magnetar, XTE J1810−197, the spectrum over 1.4–6.6 GHz is flat or rising, and we observe large, sudden changes in the pulse shape. In a contemporaneous Swift X-ray observation, 1E 1547.0−5408 was detected with record high flux, \( f_{\text{X}} \) (1–8 keV) \( \approx 5 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\), 16 times the historic minimum. The pulsar was undetected in archival radio observations from 1998, implying a flux <0.2 times the present level. Together with the transient behavior of XTE J1810−197, these results suggest that radio emission is triggered by X-ray outbursts of usually quiescent magnetars.

Subject headings: ISM: individual (G327.24−0.13) — pulsars: individual (1E 1547.0−5408, PSR J1550−5418, XTE J1810−197) — stars: neutron

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are young neutron stars with rotation periods of 5–12 s and inferred surface magnetic field strength \( B \approx 10^{14–10^{15}} \) G (see Woods & Thompson 2006 for a review). In the magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996), the rearrangement and decay of their extreme fields is responsible for the large and variable X-ray luminosity of these neutron stars, which exceeds that available from the braking of their rotation. Twelve magnetars are confirmed, of which two are in supernova remnants (SNRs). Only one magnetar, the transient 5.5 s AXP XTE J1810−197, is known to emit radio waves (Camilo et al. 2006b), with several unusual characteristics that are not understood. It is therefore important to identify further examples of this still mysterious class of neutron stars.

Discovered with the Einstein X-ray satellite in 1980, 1E 1547.0−5408 was recently identified as a magnetar candidate in the center of the small SNR G327.24−0.13 by Gelfand & Gaensler (2007), who argue convincingly against other possible classifications. Its flux, as observed by ASCA, Chandra, and XMM-Newton, has varied by a factor of 7, and it has the spectral characteristics of an AXP. Although no X-ray pulsations have been detected from 1E 1547.0−5408, the upper limit of 14% on its pulsed fraction is larger than that of one known AXP, 4U 0142+62. Here we report the discovery and initial study of radio pulsations from 1E 1547.0−5408, confirming that it is a magnetar.

2. OBSERVATIONS, ANALYSIS, AND RESULTS

2.1. Radio Pulsar Discovery

We observed 1E 1547.0−5408 with the Parkes telescope in Australia on 2007 June 8. We collected data for 20 minutes using the central beam of the multibeam receiver at a frequency \( v = 1.374 \) GHz. A bandwidth of 288 MHz was recorded, divided into 96 frequency channels sampled every 1 ms with one-bit precision. We analyzed the data using standard techniques implemented in PRESTO (Ransom et al. 2002), in similar fashion to other pulsar searches (e.g., Camilo et al. 2006a). We detected a periodic signal with \( P = 2.069 \) s that is dispersed (DM \( \approx 830 \) cm\(^{-3}\) pc) and hence of astronomical origin, which we name PSR J1550−5418.

We observed the pulsar on 11 occasions spanning 19 days, detecting it every time. The pulse profile at 1.4 GHz is very broad and asymmetric, dominated by multipath propagation in the ISM (Fig. 1). The calibrated period-averaged pulsed flux density is \( S_{\text{p}} \approx 2.5 \) mJy, with daily averaged fluxes \( S \approx 0.5 \) mJy. We measured pulse arrival times for every observation and be estimated from simultaneous multifrequency measurements. We measured pulse arrival times for every observation and obtained a phase-connected timing solution with TEMPO. The parameters from this fit are listed in Table 1.

---

1 Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027.
2 National Radio Astronomy Observatory, Charlottesville, VA 22903.
3 Australia Telescope National Facility, CSIRO, Parkes Observatory, Parkes, NSW 2870, Australia.
4 Eight AXPs and four SGRs; there are two more candidates. See catalog at http://www.physics.mcgill.ca/~pulsar/magnetar/main.html.
5 See http://www.cv.nrao.edu/~sransom/presto/
6 See http://www.atnf.csiro.au/research/pulsar/tempo/.
The position of PSR J1550–5418 was observed during the Parkes multibeam Galactic plane survey (e.g., Manchester et al. 2001). The closest pointings were made on 1998 August 8 and 13, offset by 3.1' (survey ID 4859499). We searched for pulsations in these data but found none to a limit of ≤0.5 mJy (accounting for the less sensitive beam used at an offset position). Since interstellar scintillation is not expected to modulate the flux of a pulsar with its DM (Stinebring et al. 2000), these nondetections imply that the pulsar was fainter in 1998 August than in 2007 June by a factor ≳5.

At 2 s, the rotation period of PSR J1550–5418 is substantially smaller than that of any other known magnetar. Nevertheless, its \( P \) implies a magnetic field solidly in the range of magnetars \( [B = 3.2 \times 10^{13}(PP)^{1/2} \ G = 2 \times 10^{14} \ G] \). The DM = 830 cm\(^{-3}\) pc is consistent with the large X-ray–fitted neutral hydrogen column density, \( N_h \approx 3 \times 10^{23} \) cm\(^{-2}\) (Gelfand & Gaensler 2007), and implies a distance \( d \approx 9 \) kpc according to the free-electron model of Cordes & Lazio (2002). A smaller \( d \approx 4 \) kpc for the candidate SNR G327.24–0.13 was suggested by Gelfand & Gaensler (2007). Assuming that the two objects are associated, the smaller distance estimate would place the magnetar/SNR in or near the Crux–Scutum spiral arm, while the larger distance would be compatible with a Norma spiral arm location.

The DM model also predicts a ~10 ms scattering timescale at 1.4 GHz. Instead, the ~1 s broadening observed (Fig. 1) is larger than for any known pulsar (see Bhat et al. 2004). If a portion of the unmodeled scattering were caused by electrons with larger average density in this direction than those contained in the model, then the predicted distance could be an overestimate. The 2.3 GHz profile shown in Figure 1, while much more symmetric, is still scattered, by a fitted amount ≈100 ms that is consistent with the approximate \( \nu^{-4} \) scaling.
The one mJy measurement (§ 2.1) suggests that this rising spectrum may flatten at higher frequencies, but due to the potential for variability, further measurements will be needed to address this question. We have not detected any flux from the potential for variability, further measurements will be needed to address this question. We have not detected any flux from the known magnetar. Typical values of for AXPs are among known magnetars is consistent with the hypothesis that they are born with \( P \ll 1 \) s and spin down to their longest observed periods on timescales of \( 10^4 \) yr. However, it does not ease the problem of the narrow period distribution of magnetars (Psaltis & Miller 2002), in particular, why there is a cutoff at long \( P \).

3.2. Birth Properties of 1E 1547.0–5408

The small characteristic age of PSR J1550–5418 may be related to the size of its presumed SNR G327.24–0.13, which has a diameter of \( 4'' = 4.7 (d/4 \text{ kpc}) \) pc (Gelfand & Gaensler 2007). We first argue that the SNR hosts of AXPs are no older than their pulsar’s characteristic age: the two previously confirmed AXPs that are located in remnants have characteristic age slightly larger than the SNR age (1E 1841–045; Vasishth & Gotthelf 1997), or an order of magnitude larger (1E 2259+586; Wang et al. 1992; Rho & Petre 1997). In the latter case, it is possible that the historic average of \( P \) was much higher than its present value. Similarly, G327.24–0.13 is probably not older than the \( \tau \approx P/2P = 1.4 \text{ kyr} \) of PSR J1550–5418. Then, at \( d = 4 \text{ kpc} \), the radius of the SNR shell implies an average expansion velocity of 1600 km s\(^{-1}\). This is small for the free-expansion stage of an SNR. Assuming instead that the SNR is already in the adiabatic (Sedov) phase, and following Vink & Kupfer (2006) who argued that the explosion energies of AXP remnants are no larger than those of ordinary pulsars, we find, for an explosion energy of \( 10^{51} \text{ ergs}, \) an ambient density \( \rho = 2.1 \times 10^{-22} \text{ g cm}^{-3}, \) or \( n_H = 90 \text{ cm}^{-3}, \) which is typical of molecular clouds. If the distance is 9 kpc, then the required density is \( n_H = 1.5 \text{ cm}^{-3}. \) These densities are compatible with the expectation that magnetars are born from massive stars that have short lives and are the first ones to explode, in environments that are still dense (see Gaensler et al. 2005). The larger distance, however, requires less extreme conditions than the nearer one.

The location of 1E 1547.0–5408 in the center of its presumed SNR, similar to 1E 2259+586 and 1E 1841–045, is an indication that magnetars are not born with greater kick velocity than normal pulsars. The only direct proper motion measurement of a magnetar, XTE J1810–197 with tangential velocity \( V_\perp = 212 \text{ km s}^{-1} \) (Helfand et al. 2007), supports this interpretation. We judge by eye that 1E 1547.0–5408 is within 30° of the center of the 4'' diameter shell of G327.24–0.13 (Gelfand & Gaensler 2007, Fig. 4), its presumed birth location. If its true age is equal to or greater than its characteristic age of 1.4 kyr, then its proper motion is less than 0.02'' yr\(^{-1}\). This corresponds to \( V_\perp < 900 (d/9 \text{ kpc}) \) km s\(^{-1}\).

3.3. Comparison with XTE J1810–197

Two AXPs, 1E 1547.0–5408 and XTE J1810–197, are now known to emit radio waves, and a comparison of their properties...
is revealing. Both appear to be transient. In the case of XTE J1810−197, the radio emission began within 1 yr of its only known X-ray outburst (Halpern et al. 2005). At its observed peak >3 yr after the X-ray outburst, the radio flux density was >50 times the prior upper limit (Camilo et al. 2006b), but the X-rays have now returned to quiescence, >100 times below their peak flux (Gotthelf & Halpern 2007), and the radio flux is much diminished as well (Camilo et al. 2007a). For PSR J1550−5418, we know that in 2007 June its radio flux density is >5 times the upper limit from 1998 August, while the contemporaneous X-ray flux is the highest observed. The X-ray flux history of 1E 1547.0−5408 was not as well sampled nor as consistently faint as that of XTE J1810−197, but it has varied by a factor of 16.

It may be significant that the two AXPs detected so far in radio have the smallest periods, 2.0 and 5.5 s. While X-ray emission from magnetars is manifestly not powered by rotation, it is not ruled out that their radio emission is governed by the same polar-cap gap accelerators and death lines as ordinary pulsars. If coming from open field lines, the width of the radio beam is proportional to $P^{-1/2}$, which favors detection of short-period pulsars if all are radio emitters and are randomly aligned. On the other hand, the 6.6 GHz pulse from PSR J1550−5418 (Fig. 1) is much wider than almost all profiles of ordinary long-period pulsars, so a different explanation may have to be sought for its pulse width.

If the viewing angle and magnetic inclination angle with respect to the rotation axis are both small, this could explain the broad radio pulse of PSR J1550−5418 and the failure so far to see pulsed X-ray modulation (assumed to come from surface thermal emission). It is also possible that the wide profile of PSR J1550−5418 is indicative of emission from closed, nonpotential field lines in the magnetar model (Thompson et al. 2002) instead of the narrow open field-line bundle. Closed, twisted field lines may span a large range of azimuthal angles near the surface of the neutron star, and models of pair production there yield relativistic $\gamma \sim 10^3$ that are appropriate for radio emission (Beloborodov & Thompson 2007). From XTE J1810−197, there are indications that at least some of the radio emission originates on open field lines (Camilo et al. 2007a, 2007c), while some characteristics remain unexplained and could point to either location (Camilo et al. 2007a, 2007b; Kramer et al. 2007).

Both pulsars have exhibited sudden changes in radio pulse shape. The example in Figure 2 is somewhat reminiscent of X-ray bursts from AXPs including XTE J1810−197 (Woods et al. 2005), although X-ray bursts were not seen in coincidence with such radio transitions in XTE J1810−197 (Camilo et al. 2007a). Based on the few observations so far, pulse-shape variations observed from PSR J1550−5418 are less pronounced than those in XTE J1810−197, and its daily averaged flux density may be steady, unlike the first radio magnetar (Camilo et al. 2006b, 2007a). Most striking are the flat or inverted radio spectra of PSR J1550−5418 and XTE J1810−197 (Camilo et al. 2007b), which are unique, and clearly distinguishes them from ordinary radio pulsars.

At their peak, both magnetars are very luminous young radio pulsars: $L_{1.4} \equiv S_{1.4}d^2 \approx 100$ mJy kpc$^2$, which is larger than the $L_{1.4}$ of virtually any ordinary pulsar with $\tau < 10^5$ yr (see Camilo et al. 2002). If this is a general property, the future may be (transiently) bright for further radio detections from known or yet to be identified magnetars.

We are indebted to S. Johnston, C. Phillips, G. Hobbs, and J. Verbiest for generously giving us some of their observing time, and P. Edwards for quickly approving and scheduling the observation at the ATCA. R. Bhat kindly determined the scattering timescale of the profile. We thank M. Kramer and M. Keith for providing us with archival data from the Parkes multibeam Galactic plane survey. We are grateful to the Swift project for the prompt approval and scheduling of our observing request, and to N. Mirabal for help with the analysis. The Parkes Observatory and the ATCA are part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. This work was supported in part by the NSF through grant AST 05-07376 to F. C., who also made use of the NRAO travel fund.

REFERENCES

Baykal, A., & Swank, J. 1996, ApJ, 460, 470
Beloborodov, A. M., & Thompson, C. 2007, ApJ, 657, 967
Bhat, N. D. R., Cordes, J. M., Camilo, F., Nice, D. J., & Lorimer, D. R. 2004, ApJ, 605, 759
Camilo, F., Manchester, R. N., Gaensler, B. M., Lorimer, D. L., & Sarkissian, J. 2002, ApJ, 567, L71
Camilo, F., Ransom, S. M., Gaensler, B. M., Slane, P. O., Lorimer, D. R., Reynolds, J., Manchester, R. N., & Murray, S. S. 2006a, ApJ, 637, 456
Camilo, F., Ransom, S. M., Halpern, J. P., Reynolds, J., Helfand, D. J., Zimmermann, N., & Sarkissian, J. 2006b, Nature, 442, 892
Camilo, F., et al. 2007a, ApJ, 663, 497
———. 2007b, ApJ, in press (arXiv:0705.4095)
———. 2007c, ApJ, 659, L37
Cordes, J. M., & Lazio, T. J. W. 2002, preprint (astro-ph/0207156)
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Gaensler, B. M., McClure-Griffiths, N. M., Oey, M. S., Haverkorn, M., Dickey, J. M., & Green, A. J. 2005, ApJ, 620, L95
Gelfand, J. D., & Gaensler, B. M. 2007, ApJ, 667, in press (arXiv:0706.1054)
Gotthelf, E. V., & Halpern, J. P. 2007, ApSS, 308, 79
Halpern, J. P., Gotthelf, E. V., Becker, R. H., Helfand, D. J., & White, R. L. 2005, ApJ, 632, L29
Helfand, D. J., Chatterjee, S., Brisken, W., Camilo, F., Reynolds, J., van Kerkwijk, M. H., Halpern, J. P., & Ransom, S. M. 2007, ApJ, 662, 1198
Koyama, K., et al. 1989, PASJ, 41, 461
Kramer, M., Stappers, B. W., Jessner, A., Lyne, A. G., & Jordan, C. A. 2007, MNRAS, 377, 107
Manchester, R. N., et al. 2001, MNRAS, 328, 17
Mereghetti, S., et al. 2005, ApJ, 628, 938
Psaltis, D., & Miller, M. C. 2002, ApJ, 578, 325
Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, AJ, 124, 1788
Rho, J., & Petre, R. 1997, ApJ, 484, 828
Sinebring, D. R., Smirnova, T. V., Hankins, T. H., Hovis, J., Kaspi, V., Kempner, J., Meyers, E., & Nice, D. J. 2006, ApJ, 599, 300
Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255
———. 1996, ApJ, 473, 322
Thompson, C., Lyutikov, M., & Kulkarni, S. R. 2002, ApJ, 574, 332
Vasilish, G., & Gotthelf, E. V. 1997, ApJ, 486, L129
Vink, J., & Kuiper, L. 2006, MNRAS, 370, L14
Wang, Z., Qu, Q., Luo, D., McCray, R., & Mac Low, M.-M. 1992, ApJ, 388, 127
Woods, P. M., & Thompson, C. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 547
Woods, P. M., et al. 2005, ApJ, 629, 985
Yakovlev, D. G., Kaminker, A. D., Haensel, P., & Gnedin, O. Y. 2002, A&A, 389, L24