DISCOVERY OF THE X-RAY COUNTERPART TO THE ROTATING RADIO TRANSIENT J1819−1458

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ABSTRACT

We present the discovery of the first X-ray counterpart to a Rotating RAdio Transient (RRAT) source. RRAT J1819−1458 is a relatively highly magnetized ($B = 5 \times 10^{13} \text{ G}$) member of a new class of unusual pulsar-like objects discovered by their bursting activity at radio wavelengths. A Chandra observation of that position revealed a pointlike source, CXOU J181934.1−145804, with a soft spectrum well fit by an absorbed blackbody with $N_H = 7^{+4}_{−2} \times 10^{21} \text{ cm}^{-2}$, temperature $kT = 0.12 \pm 0.04 \text{ keV}$, and an unabsorbed flux of $\sim 2 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ between 0.5 and 8 keV. No optical or infrared (IR) counterparts are visible within 1' of our X-ray position. The positional coincidence, spectral properties, and lack of an optical/IR counterpart make it highly likely that CXOU J181934.1−145804 is a neutron star and is the same object as RRAT J1819−1458. The source showed no variability on any timescale from the pulse period of 4.26 s up to the 5 day window covered by the observations, although our limits (especially for pulsations) are not particularly constraining. The X-ray properties of CXOU J181934.1−145804, while not yet measured to high precision, are similar to those of comparably aged radio pulsars and are consistent with thermal emission from a cooling neutron star.

Subject headings: pulsars: individual (J1819−1458) ⋅ radio continuum: stars ⋅ stars: neutron ⋅ X-rays: stars

1. INTRODUCTION

The discovery of a new class of “Rotating RAdio Transients” (RRATs) has recently been reported by McLaughlin et al. (2006). These objects, 11 so far identified, are characterized by repeated radio bursts with durations between 2 and 30 ms and average intervals between bursts ranging from 4 minutes to 3 hr. Their dispersion measures (DMs) place them within the Galactic plane at distances from 2 to 7 kpc. If bursts are periodic, periods can be found from the greatest common divisor of the differences between burst arrival times. For 10 of the sources, this calculation results in periods between 0.4 and 7 s, suggesting that the objects are rotating neutron stars. The periods measured for the RRATs are longer than those of most normal radio pulsars and more similar to those of the populations of X-ray-dim isolated neutron stars (XDINs; Haberl 2004) and magnetars (Woods & Thompson 2006). For the three sources with the highest bursting rates, period derivatives, $\dot{P}$, have been measured. No binary motion is detected. If the $\dot{P}$ values are interpreted as being due to magnetic dipole spin-down, they imply characteristic ages and magnetic field strengths in the general range of pulsars.

In this Letter we report the X-ray detection of RRAT J1819−1458, the first detection at other wavelengths of any of the RRATs. This source has a 4.26 s period, a relatively high inferred characteristic surface dipole magnetic field strength of $5 \times 10^{13} \text{ G}$, a characteristic age $P/\dot{P} = 117 \text{ kyr}$, and a spin-down luminosity of $3 \times 10^{32} \text{ ergs s}^{-1}$. Its distance, inferred from its DM using the electron-density model of Cordes & Lazio (2002), is 3.6 kpc, with considerable uncertainty. RRAT J1819−1458 is characterized by radio bursts of an average duration of 3 ms, with one burst detected every $\sim$3 minutes. This object was fortuitously in the ACIS-I field of a 30 ks Chandra observation toward the Galactic supernova remnant G15.9+0.2 (S. P. Reynolds et al. 2006, in preparation). The brightest source on any of the six CCD chips of the Chandra field, besides G15.9+0.2 itself, is coincident to within 2" with the radio position of RRAT J1819−1458 (whose error ellipse has semimajor axes $5'' \times 32'').$ The positional coincidence as well as the properties we describe below make us confident that this new source, which we designate CXOU J181934.1−145804, is the X-ray counterpart to the radio-bursting source RRAT J1819−1458.

2. OBSERVATIONS

The Chandra observations were performed with the ACIS instrument in full-frame mode on 2005 May 23 (10 ks), May 25 (5 ks), and May 28 (15 ks). CXOU J181934.1−145804 lies on the I3 chip of the ACIS-I camera. We checked the aspect correction, created a new level-1 event file appropriate for VFAINT mode (without applying pixel randomization in energy), and applied light-curve filtering to reject flares. CTI correction was applied, and calibration was performed, using CALDB version 3.1.0. CXOU J181934.1−145804 is by far the brightest compact source on the I3 chip or on any of the others. We find a net count rate after background subtraction of 0.018 counts s$^{-1}$.
(0.5–8 keV), for a total of 524 ± 24 counts. Radial profiles were created for the source and for the 1 keV point-spread function (PSF) at that location on the I3 chip, and they are shown in Figure 1. There is no evidence for any extended emission. The source position (fit with wavdetect) is 18h19m34.17 ± 0.02, −14°58′04.76 ± 0′′2 (J2000). The errors are statistical only. We measured the position of a bright star visible in X-rays to be within 0′′1 of its USNO UCAC2 position, but position errors for sources 10′ off-axis may be ≤0′′4 (Getman et al. 2005). We adopt 0′′5 as a conservative total error estimate.

We searched various catalogs for optical or IR counterparts within 1″ of our best-fit position. No counterparts were detected in the Two Micron All Sky Survey (2MASS) catalog or in any of the others that we searched using Vizier,11 with magnitude upper limits of 19.9 (B2), 18.0 (R1), 17.5 (I), 15.6 (J), 15.0 (H), and 14.0 (K). Nothing was seen in the Galactic Legacy Mid-Plane Survey Extraordinaire (G L M P E S), which used Spitzer’s Infrared Array Camera (Benjamin et al. 2003), but the limits are comparable or less stringent. We expect a surface density of Galactic plane X-ray sources of at least the flux of CXOU J181934.1–145804 of about 2 deg−2, based on the ASCA Galactic Plane survey (Sugizaki et al. 2001). Within the radio error ellipse of RRAT J1819−1458, the likelihood of finding such a source by chance is ≤10−4, supporting its identification with RRAT J1819−1458.

The K-magnitude limit from 2MASS, combined with our X-ray detection, implies an X-ray–to–IR flux ratio for CXOU J181934.1–145804 of 1.5 ± 0.7. Comparing this to the known X-ray and IR properties of stars, galaxies, and neutron stars (see, e.g., Fig. 20 of Kaplan et al. 2004), we find that CXOU J181934.1–145804 has a much higher X-ray–to–IR flux ratio than most stars, especially given the higher absorption toward CXOU J181934.1–145804. Furthermore, in that direction (l, b = (16°0, 0′08)), we expect a total Galactic column density of N_H ≥ 2 × 10^23 cm−2 [e.g., from COLDEN for V(H1)], far larger than we observe (see next section), indicating that CXOU J181934.1–145804 is within a few kiloparsecs. The soft spectrum even with relatively low absorption is unlike any known active galactic nucleus. However, the flux and colors are entirely consistent with all classes of isolated neutron star. Deeper IR and optical observations are needed to provide better constraints.

There is no X-ray evidence for a supernova remnant (SNR), pulsar wind nebula, or any other extended emission anywhere within about 7″ of CXOU J181934.1−145804.

3. SPECTRAL ANALYSIS

We extracted the source spectrum from a circular region 15″ in radius centered at the X-ray source position. Individual response files were created for the source and for a large (~3 × 3″) adjacent background region. Data from all three observations were merged by adding spectra and combining the response files weighted by observation times (for both source and background), and then grouped into bins of at least 20 counts to allow the use of χ^2 statistics.

An absorbed blackbody fit (XSPEC models phabs plus bbodyrad) was statistically acceptable (χ^2 = 10.8 for 18 degrees of freedom); it is shown in Figure 1. An absorbing column density N_H = 7.4 × 10^21 cm−2 was required (all errors are 90% confidence limits unless otherwise specified). The fitted temperature is kT = 0.12 ± 0.04 keV, and the observed flux (0.5–8 keV) is (1.1 ± 0.1) × 10^{-13} ergs cm−2 s−1. The absorption-corrected flux is much less certain due to uncertainties in N_H; we find a flux (0.5–8 keV) of ∼2 × 10^{-12} ergs cm−2 s−1, with uncertainty of an order of magnitude in either direction.

A blackbody with the best-fit flux would have a radius of 10 km at a distance of 1.8 kpc; at the DM distance of 3.6 kpc, the implied blackbody radius is 20 km. Note that, given the uncertainties in DM-derived distances (Cordes & Lazio 2002), a distance of 1.8 kpc is still consistent with the observed DM. The X-ray luminosity is 3.6 × 10^{31}(D/3.6 kpc)^2 ergs s−1 (0.5–8 keV) (uncertain by an order of magnitude), although of course most of the bolometric luminosity is at lower photon energies (a spherical blackbody with kT = 0.12 keV and R = 10 km has a total luminosity L_{bol} = 2.7 × 10^{31} ergs s−1). We also fit the data with a neutron star atmosphere model (XSPEC model nsa: Pavlov et al. 1991; Zavlin et al. 1996), obtaining a slightly worse but acceptable (χ^2 = 0.66) fit with N_H = (0.4–1.3) × 10^{21} cm−2, kT_{eff} = 0.02–0.2 keV, and a flux corresponding to roughly full-surface emission from a 10 km neutron star at 1.8 kpc. These values are completely consistent with those of the simple blackbody fit.

An absorbed power-law fit (XSPEC models phabs plus power) was significantly worse (Δχ^2 = 3.9, or worse at the 95% level). In addition, the power-law fit required a photon index Γ of at least 9.5, far steeper than any observed magnetospheric or other nonthermal X-ray emission from any known source. However, a nonthermal component at higher energies might be present in addition to the thermal emission. To search for such a component, we fitted only the data above 1 keV, and we obtained a best-fit power-law index of 5.5, still unreasonably steep. There appears to be no evidence for a nonthermal component in the X-ray spectrum of CXOU J181934.1–145804, at our current level of sensitivity. We note that even with the large uncertainties, L_{bol} > E independent of distance, making a nonthermal explanation for most of the emission highly unlikely.

4. TIMING ANALYSIS

The time resolution of Chandra’s CCDs in imaging mode is 3.2 s, the readout time. We binned the light curve on a variety
of timescales to look for evidence of bursts or other time variability on scales longer than this.

We have examined all $\sim 10^4$ of the 3.2 s CCD frames of the source extraction region to look for any bursts resembling the radio bursts (McLaughlin et al. 2006). Pileup is not a concern because of the substantially broadened off-axis PSF. All frames contained either zero events or one event, except for 17 frames that contained two events from the source and one frame that contained a cluster of three events. For the time-averaged count rate of $\sim 0.05$ counts per frame, these clusters are entirely consistent with Poisson statistics. Given this rate, the number of events in a single frame that would deviate from a steady flux is a single frame that would deviate from a steady flux at the 3 $\sigma$ level is 4 photons. We thus adopt this as the upper limit on the X-ray flux of any burst of duration of 3.2 s or less. Assuming a spectrum of the same shape as that fitted for the overall source in § 3, this limits the observed fluence of any burst to $\leq 3 \times 10^{-11} \text{ ergs cm}^{-2}$ (0.5–8 keV), corresponding to an absorbed flux limit of $\leq 1 \times 10^{-8} \text{ ergs cm}^{-2}$ s$^{-1}$ if we assume that any X-ray burst lasts for 3 ms. At a distance of 3.6 kpc, these limits correspond to $1 \times 10^{36}$ ergs and $1 \times 10^{38}$ ergs s$^{-1}$, respectively. A burst might, of course, have a very different spectrum from that seen in Figure 1.

We have also binned the data on longer timescales to look for any more gradual variability. At the 3 $\sigma$ level, we find no evidence for X-ray flux variations on any timescale ranging from 3.2 s up to the overall time span covered of $\sim 5$ days. We note, however, that data were only being recorded during 7% of this window, so within the range of variability considered, we are not sensitive to variations on timescales falling between $\sim 4$ hr and $\sim 2$ days.

While we cannot detect pulsations at the 4.26 s period directly, we searched for a possible alias of this period at a predicted frequency of 0.07375824(1) Hz (correcting for spin-down and barycentered to the midpoint of the three observations). We folded the arrival times at this frequency and found no significant power. Including attenuation of sensitivity at frequencies high compared to the binning rate, our 3 $\sigma$ upper limit on the pulsed fraction $f$ is $\sim 0.5 A^{-1/2}$, where $A$ is a constant that depends on the pulse shape (Leahy et al. 1983; Ransom et al. 2002). For a narrow pulse ($A = 2$) as observed in the radio bursts, we estimate $f \leq 0.35$, while for a sinusoid ($A = 0.5$), we find $f \leq 0.7$.

5. DISCUSSION

The spatial coincidence of RRAT J1819$-$1458 and CXOU J181934.1$-$145804 and the lack of any obvious optical or infrared counterpart make it extremely likely that these sources are associated and that the emitting source is a neutron star. We now compare the X-ray and other properties of RRAT J1819$-$1458 to those of the other categories of isolated neutron stars: radio pulsars, magnetars, XDINSs, and central compact objects (CCOs).

We first note that the pulsed fraction upper limits that we obtained in § 4 are generally unconstraining. Pulsed thermal emission from a “hot spot” on a neutron star surface is expected to be broad and quasi-sinusoidal, with a low level of modulation (Kaspi et al. 2006). Thus, the pulsed fraction upper limit of $\sim 70\%$ that we have determined for a broad profile is insufficient to have detected pulsations from almost all the sources that we consider below.

Over much of their lives, ordinary radio pulsars emit quasi-blackbody emission from their surfaces, the temperature dropping with time as they cool through first neutrino, then photon emission (see Yakovlev & Pethick 2004 for a recent review). A 1.4 $M_{\odot}$ neutron star at an age of $10^4$ yr is predicted by typical models to have a surface temperature (as viewed by an observer at infinity) $\sim 100$ eV, while by $10^5$ yr this has dropped to $\sim 70$ eV (Page et al. 2004; Yakovlev & Pethick 2004). The X-ray emission from neutron star surfaces is expected to be significantly modified by propagation through the stellar atmosphere, which shifts the emission into a harder component (Zavlin & Pavlov 2002; Lloyd et al. 2003). Applied to such spectra, blackbody fits overestimate the surface temperature by a factor of $\geq 2$ and also underestimate the radius.

While we are sufficiently precise to fit the more detailed neutron star atmosphere models, the considerations above suggest that the emission from RRAT J1819$-$1458 is consistent with a cooling neutron star of age $\sim 10^4$–$10^5$ yr, at a distance $\leq 2$ kpc.12 For comparison, the radio pulsars B0833$-$45, B1706$-$44, J2021+3651, J0538+2817, and B0656$+$14 have fitted blackbody temperatures of 130, 170, 150, 160, and 70 eV for approximate ages of 11, 17, 17, 30, and 110 kyr, respectively (Romani et al. 2005; Hessels et al. 2004; Romani & Ng 2003; Kramer et al. 2003; Brinken et al. 2003). While the temperature that we find for CXOU J181934.1$-$145804 is a bit higher than that of the comparably aged B0656$+$14, our errors are large. Better data will be required to determine whether CXOU J181934.1$-$145804 is in fact hotter than the range of predictions from standard cooling curves. The high magnetic field strength might support such a possibility (Shibanov & Yakovlev 1996).

These crude estimates are in satisfactory agreement with the characteristic age, $\tau = 117$ kyr, inferred for RRAT J1819$-$1458 from its spin-down (McLaughlin et al. 2006). If RRAT J1819$-$1458 was born spinning much faster than its present period of 4.26 s, then for standard magnetic dipole spin-down, the characteristic age should be a good match to the true age. If it was born a slow rotator, then $\tau$ could be a considerable overestimate (e.g., Kramer et al. 2003).

The surface magnetic field of RRAT J1819$-$1458 is about 10 times greater than those of the pulsars listed above. The two high $B$-field pulsars (Camilo et al. 2000; McLaughlin et al. 2003) detected in X-rays, PSR J1718$-$3719 and PSR J1119$-$6127 (Kaspi & McLaughlin 2005; Gonzalez et al. 2005), also show temperatures ($kT \sim 150$–200 eV) and luminosities ($\sim 10^{31}$–$10^{33}$ ergs s$^{-1}$) compatible with that of RRAT J1819$-$1458, although both sources are probably much younger (35 and 1.7 kyr, respectively) and have $L_x < \dot{E}$.

The high inferred surface magnetic field strength, long spin period, and lack of persistent radio emission also suggest a comparison with magnetars. These objects (which include both anomalous X-ray pulsars and soft gamma repeaters) are characterized by quiescent, bursting, and flaring X-ray emission all powered in different ways by ultrastrong magnetic fields (Woods & Thompson 2006 and references therein). However, magnetars are typically hotter ($kT \sim 0.3$–0.6 keV), show a non-thermal spectral component with $\Gamma \sim 2$–4, and are brighter by 1–3 orders of magnitude ($L_x \sim 10^{34}$–$10^{36}$ ergs s$^{-1}$; Woods & Thompson 2006). Moreover, the characteristics of the radio bursts seen from RRAT J1819$-$1458 and from the other RRATs are completely different in their energetics and recurrence times from the much rarer X-ray bursts seen from the magnetars. The soft X-ray spectrum of RRAT J1819$-$1458 does have a comparable temperature to the quiescent state of the transient magnetar XTE J1810$-$197 ($kT \sim 0.15$–0.18 keV; Ibrahim et al. 2004; Gotthelf et al. 2004). However, the X-ray

12 Our result that $L_x \sim \dot{E}$ for this source is not consistent with polar-cap reheating models for the thermal X-rays seen for much older sources (e.g., Cheng & Zhang 1999; Harding & Muslimov 2001).
luminosity of the latter is ~10 times larger. XTE J1810−197 also has a possible transient radio counterpart (Halpern et al. 2005), although with quite different properties from the RRATs. Further observations are required for a detailed comparison with RRAT J1819−1458.

The lack of persistent radio emission and the long spin period of RRAT J1819−1458 also raise the possibility of a link with the XDINSs (Haberl 2004). The XDINSs are slightly cooler ($kT \sim 0.04–0.1$ keV) and less luminous ($L_\gamma \sim 10^{39}–10^{40}$ ergs s$^{-1}$) than RRAT J1819−1458. However, the measured period derivatives of two XDINSs (RBS 1223 and RX J0720.4−3125; Kaplan & van Kerkwijk 2005a, 2005b), and the detection of possible proton-cyclotron lines in their spectra (van Kerkwijk 2004), imply magnetic field strengths similar to those of RRAT J1819−1458. No radio emission of any kind has been reported from XDINSs; recent observations (Bradley 2006) show no RRAT-like radio bursts toward RX J0720.4−3125 (or toward magnetars).

RRAT J1819−1458 does not appear to have an associated SNR. It has no apparent connection to the nearby SNR G15.9+0.2 (see below) and shows no extended radio or X-ray emission. Nevertheless, for completeness we compare its X-ray emission to that seen from the CCOs, a small and heterogeneous sample of X-ray point sources seen in young SNRs, apparently young neutron stars whose connection to pulsars, magnetars, and XDINSs is as yet unclear (see Pavlov et al. 2004 for a review). The CCOs have spectra that can generally be fitted by a blackbody plus a power-law tail, the former component having a temperature $kT \approx 0.3–0.5$ keV with a typical bolometric luminosity $L_{bol} \approx 10^{33}$ ergs s$^{-1}$. Periodicities have been reported for four of the CCOs, but with periods much faster (100–400 ms) or much slower (~6 hr) than seen for RRAT J1819−1458. The properties of RRAT J1819−1458 thus seem to have little in common with those seen from the CCOs, although RRAT J1819−1458 is likely much older than these objects, and the evolutionary paths followed by the CCOs are unclear in any case.

The shell SNR G15.9+0.2 has a much higher absorbing column density ($\sim 4 \times 10^{22}$ cm$^{-2}$) than CXOU J181934.1−145804, suggesting that it is at a considerably greater distance. In any case, G15.9+0.2 appears to be younger than 1000 yr (S. P. Reynolds et al. 2006, in preparation), so disregarding the much older spin-down age of RRAT J1819−1458 and hypothesizing an association, the 10.3 offset between RRAT J1819−1458 and the center of G15.9+0.2 requires a transverse velocity for the former of $\sim 10,000$ km s$^{-1}$ at a distance of 3.6 kpc. This makes any physical association of G15.9+0.2 with RRAT J1819−1458 highly improbable.

6. Conclusions

We have discovered the first X-ray counterpart to an RRAT (Rotating Radio Transient) source, CXOU J181934.1−145804. The X-ray source is well described by a thermal spectrum consistent with emission from a cooling neutron star of age $10^8–10^9$ yr, broadly consistent with the characteristic age of RRAT J1819−1458. The X-ray properties also suggest possible connections to the population of X-ray-dim isolated neutron stars and to the transient magnetar XTE J1810−197. A search for an X-ray modulation at the aliased radio pulse frequency was unsuccessful. No variations were seen in the X-ray flux on longer timescales either, and no optical or infrared counterparts to the source have been found. Deeper X-ray observations are required to search for pulsations, bursts, and in general to clarify the nature of the RRATs.

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