Upper limits on X-ray emission from two rotating radio transients

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Upper Limits on X-ray Emission from Two Rotating Radio Transients

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ABSTRACT

X-ray emission from the enigmatic Rotating RAdio Transients (RRATs) offers a vital clue to understanding these objects and how they relate to the greater neutron star population. An X-ray counterpart to RRAT J1819−1458 is known, and its properties are similar to those of other middle-aged (0.1 Myr) neutron stars. We have searched for X-ray emission with Chandra/ACIS at the positions of two RRATs with arcsecond (or better) localisation, J0847−4316 and J1846−0257. Despite deep searches (especially for RRAT J1846−0257) we did not detect any emission with 0.3–8 keV count-rate limits of 1 counts ks−1 and 0.068 counts ks−1, respectively, at 3σ confidence. Assuming thermal emission similar to that seen from RRAT J1819−1458 (a blackbody with radius ≈20 km), we derive effective temperature limits of 77 eV and 91 eV for the nominal values of the distances and column densities to both sources, although both of those quantities are highly uncertain and correlated. If we instead fix the temperature of the emission (a blackbody with kT=0.14 keV), we derive unabsorbed luminosity limits in the 0.3–8 keV range of 1 × 1032 erg s−1 and 3 × 1032 erg s−1. These limits are considerably below the luminosity of RRAT J1819−1458 (4 × 1033 erg s−1), suggesting that RRATs J0847−4316 and J1846−0257 have cooled beyond the point of visibility (plausible given the differences in characteristic age). However, as we have not detected X-ray emission, it may also be that the emission from RRATs J0847−4316 and J1846−0257 has a different character from that of RRAT J1819−1458. The two non-detections may prove a counterpoint to RRAT J1819−1458, but more detections are certainly needed before we can begin to derive general X-ray emission properties for the RRAT populations.

Key words: pulsars – stars: neutron – X-rays: stars

1 INTRODUCTION

The radio-transient sky is one of the least explored frontiers in astronomy. There have been many searches for transient signals, but few astrophysical sources of radio bursts have been confirmed (Cordes, Lazio & McLaughlin 2004; Hyman et al. 2003). However, McLaughlin et al. (2006) reported the discovery of eleven objects characterised by the recurring although unpredictable emission of single, dispersed radio pulses (additional objects have been discovered...
by [Deneva et al. 2009] and others). The unique dispersion measures identified them as astronomical signals, and the peak flux densities (ranging from 100 mJy to 3.6 Jy) made these transients among the brightest radio sources in the universe. The most natural interpretation of these sources is that they are rotating neutron stars (NSs) which emit radio bursts sporadically: hence the name Rotating Radio Transients (RRATs).

Based on their ephemeral nature, the total number of RRATs in the Galaxy (∼ 10^5; [McLaughlin et al. 2006; Keane & Kramer 2008]) might exceed that of the radio pulsars, thus representing a large fraction of the population of neutron stars with age smaller than ∼ 10^7 yr. That calls for a deep investigation of these objects, aimed at understanding their emission properties, environments, and evolutionary links (if any) with other classes of neutron stars. It has been proposed that RRATs could be an extreme manifestation of processes already observed in at least some ordinary pulsars: e.g., giant pulses ([Knight et al. 2006]), nulling ([Zhang, Gil & Dyks 2007]), or the fading of the radio signal of an old pulsar while approaching the pair-production death line ([Zhang et al. 2007]). A particularly interesting hypothesis is that RRATs may be distant middle-aged (spin-down ages 1–5 × 10^6 yr) ordinary pulsars (such as PSR B0656+14), whose emission is only detectable when particularly bright pulses occur ([Weltz & Krueger et al. 2008]). According to other models, the RRATs do not belong to the population of the rotation-powered pulsars: instead associations with the steadily-emitting magnetars (e.g., [McLaughlin et al. 2006]), transient magnetars ([McLaughlin et al. 2009]), or thermally-emitting isolated neutron stars (INS) ([Popov, Turolla & Possenti 2006]) were suggested. Even more exotic hypotheses explain the bursting behavior of the RRATs with the sporadic effects of an asteroid or radiation belt surrounding the pulsar (e.g., [Li 2006; Cordes & Shannon 2008; Luo & Melrose 2007]).

The observation of the counterpart to a RRAT in the X-ray band could be crucial for discriminating between many of the models reported above, since they predict distinct X-ray spectral signatures for the source. Unfortunately, only RRAT J1819–1458 (with spin period P = 4.26 s, dipole magnetic field B = 5 × 10^13 G, characteristic age τ = 1.2 × 10^7 yr, and spin-down luminosity \( \dot{E} = 3 \times 10^{32} \text{erg s}^{-1} \); for definitions of these parameters see [Lorimer & Kramer 2004]) has been detected at high energies. It was serendipitously found in Chandra observations of the (almost certainly unrelated) supernova remnant G15.9+0.2. Additional long pointed integrations revealed that RRAT J1819–1458 has a thermal spectrum with \( kT = 0.14 \text{keV} \) and an unabsorbed X-ray luminosity \( L_X \approx 4 \times 10^{33} \text{erg s}^{-1} \) ([McLaughlin et al. 2007]), which is larger than the spin-down luminosity. The spectrum differs from that of the magnetars, which are hotter (\( kT \sim 0.3 - 0.6 \text{keV} \) [Woods & Thompson 2006], although it may be similar (at times) to that of the transient magnetar XTE J1810–197 (\( kT \sim 0.15 - 0.18 \text{keV} \); [Ibrahim et al. 2004; Gotthelf & Halpern 2004]). Instead, the spectrum of RRAT J1819–1458 is comparable in temperature ([Koptsevich et al. 2001]) and X-ray luminosity to the similarly-aged radio pulsar B0556+14 (which itself is consistent with being a nearby RRAT; see above). It is also similar to the slightly older radio-quiet INS (\( kT = 0.05 - 0.1 \text{keV} \) at ages of \( \approx 0.5 \) Myr; see [Haberl 2007; Kaplan 2008]). In addition, the spectrum displays a broad absorption line ([McLaughlin et al. 2007]) resembling the lines detected in many of the INS ([Haberl 2007; van Kerkwijk & Kaplan 2007]).

The case of RRAT J1819–1458 illustrates the potentiality of X-ray observations in unveiling possible connections between RRATs and other NS populations. However, until recently these studies have been significantly limited by the lack of precise positions for most of the sources. RRAT J1819–1458 was one of the only three RRATs whose celestial coordinates had been precisely determined through pulse timing (e.g., as discussed in [Lorimer & Kramer 2004]). All the other RRATs were only localised to within the primary beam of the Parkes telescope: ∼ 14 arcmin diameter for the observing frequency of 1.4 GHz. That prevented follow-up multi-wavelength observations and, in turn, the possibility of constraining the spectrum of the RRATs and their primary energy stores.

Dedicated timing observations presented in [McLaughlin et al. 2009] have more than doubled the sub-sample of the RRATs with phase-connected timing solutions and hence high precision rotational and astrometric parameter. Two among the RRATs with a new timing solution (J0847–4316 and J1456–0257) are located in the \( P - \dot{P} \) diagram in a region almost devoid of ordinary pulsars (see Section 2 for timing parameters) but close to the area occupied by the INS, lending support to the hypothesis ([Keane & Kramer 2006; McLaughlin et al. 2009]) that they could be transition objects between ordinary pulsars and INS.

Inspecting the \( P - \dot{P} \) diagram (see e.g., Figure 4 in [McLaughlin et al. 2009]), J0847–4316 and J1456–0257 also appear the closest RRATs to the location of J1819–1458, the only RRAT detected in X-ray so far (see above). Here we present searches for X-ray emission from these two particularly promising sources, based on targeted and archival Chandra observations. In what follows, all luminosities are corrected for interstellar absorption.

2 OBSERVATIONS AND UPPER LIMITS

2.1 RRAT J0847–4316

We searched for an X-ray counterpart to RRAT J0847–4316 (\( P = 5.978 \text{s}, B = 3 \times 10^{13} \text{G}, \tau = 0.8 \text{Myr}, \text{and} \dot{E} = 2 \times 10^{32} \text{erg s}^{-1} \)) with the Chandra X-ray Observatory ([Weisskopf et al. 2000]), as summarised in Table 1. As the position was originally only known to ±7 arcmin, we used the 16 arcmin\(^2\) imaging array on the Advanced CCD Imaging Spectrometer (ACIS-I, [Garmire et al. 2003]). The data were

\[^{1}\] These timing solutions were derived by fitting a timing model to pulse times-of-arrival using TEMPO, as is done for normal radio pulsars, but using single pulses rather than average profiles. To avoid underestimating the positional uncertainties, the quoted 1-σ positional uncertainties have been calculated by requiring the reduced \( \chi^2 \) values of the residuals to be equal to one (see [McLaughlin et al. 2009] for more details). As a confirmation of the accuracy of this technique, we note that the position of the X-ray counterpart to RRAT J1819–1458 (confirmed via the identical periodicity of its X-ray pulsations) is well within the radio timing error circle ([McLaughlin et al. 2006; Rea et al. 2009]).
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Figure 1. Chandra images of RRATs J0847−4316 and J1846−0257 in the 0.3−8.0 keV band. Left: 10.7 ks Chandra/ACIS-I1 image of RRAT J0847−4316. Right: 158.3 ks Chandra/ACIS-S3 image of RRAT J1846−0257, created from summing the observations from 2006 in Table 1. Overlaid on each is the region (2 arcsec radius circle) selected for the analysis (see text). Both images are 15 arcsec square, with north up and east to the left. A 5 arcsec scale bar is in the lower left of each image.

Table 1. Summary of X-ray Observations

<table>
<thead>
<tr>
<th>RRAT</th>
<th>ObsID</th>
<th>Date</th>
<th>Detector</th>
<th>Exp. (ks)</th>
<th>Off-Axis Angle (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0847−4316</td>
<td>7626</td>
<td>2007-02-08</td>
<td>ACIS-I</td>
<td>10.7</td>
<td>1.1</td>
</tr>
<tr>
<td>J1846−0257</td>
<td>748</td>
<td>2000-10-15</td>
<td>ACIS-S</td>
<td>37.8</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>6986</td>
<td>2006-06-07</td>
<td>ACIS-S</td>
<td>55.3</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>7337</td>
<td>2006-06-05</td>
<td>ACIS-S</td>
<td>17.8</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>7338</td>
<td>2006-06-09</td>
<td>ACIS-S</td>
<td>40.1</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>7339</td>
<td>2006-06-12</td>
<td>ACIS-S</td>
<td>45.1</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The first two observations were taken in the default Faint mode and with a 3.2 s frame time. The remaining observations were taken in the Very Faint mode, and with a 1.8 s frame time to reduce the effect of pileup on the probably unrelated PSR J1846−0258; see Helfand, Collins & Gotthelf (2003) and Ng et al. (2008).

The position is near a gap between CCDs of the ACIS-I detector, but is not in the gap: examination of the exposure map (which takes into account effective area maps of each detector as well as the dither pattern of Chandra on the sky) shows an effective area at the position of RRAT J0847−4316 comparable to the average of the ACIS-I CCD. However, we see no source at the position of RRAT J0847−4316, and searches using wavdetect did not find any source closer than 1.5 arcmin. We must go out to a radius of > 1 arcsec before there are any counts, and those counts appear consistent with the background rate (0.0300 ± 0.0010 counts arcsec$^{-2}$). We compare this with the radio position uncertainty (∼0.6 arcsec), the Chandra aspect uncertainty (0.6 arcsec at 90 per cent confidence, as this source is on-axis; there is no systematic aspect offset listed for this observation), and the Chandra point-spread function (90 per cent encircled energy radius of ∼1 arcsec at 1.5 keV). Using a generous extraction radius of 2 arcsec there are 2 counts with 0.4 expected from the background (see Figure 1). Given Poisson fluctuations (Gehrels 1986), we can place a 3σ upper limit of ∼10 counts coming from RRAT J0847−4316, or a count-rate limit of ∼1 counts ks$^{-1}$.

Note that for RRAT J1819−1458 about 10 per cent of the X-ray flux is in an extended nebula going out to at least 13 arcsec (Rea et al. 2009), but the contribution is small enough that our limits are not affected by the size of our extraction region.

2.2 RRAT J1846−0257

The field of RRAT J1846−0257 ($P = 4.477$ s, $B = 3 \times 10^{13}$ G, $\tau = 0.4$ Myr, and $\dot{E} = 7 \times 10^{31}$ ergs s$^{-1}$) has been imaged by various X-ray instruments during observations targeting the probably unrelated (see Section 3) X-ray pulsar PSR J1846−0258 and its supernova remnant Kes 75 (Gavriil et al. 2008 and references therein). Among the available data, those collected with Chandra are the best suited to search for X-ray emission from RRAT J1846−0257 because of the superb angular resolution. Five observations were carried out between 2000 and 2006 (see Table 1 with the source positioned on the back-illuminated...
ACIS-S3 chip. We again reduced the data using CIAO, applying aspect corrections and filtering the data to reject time intervals of flaring background as necessary; see Helfand et al. (2004) and Ng et al. (2008) for detailed information about the datasets. Figure 4 shows the image from the combined data. Source detection was performed with the CELLDTECT and WAVEDTECT routines in CIAO over numerous energy bands on each individual dataset and on a cumulative image that was obtained from the 2006 observations with a total exposure of 158 ks. No X-ray source was found near the RRAT J1846–0257 radio position (J2000: 18°46′15.49″ ± 0.04″, −02°37′36.0″ ± 1″). As with RRAT J0847–4316 we used a generous search radius of 2 arcsec, which combines the radio position uncertainty, the Chandra position uncertainty and the Chandra point-spread function. Based on the 8 events within this circle (background expectation is 7), this upper limit is $6.8 \times 10^{-2}$ counts ks$^{-1}$ in the 0.3–8 keV energy band, at 3σ confidence level (again based on Gehrels 1986).

2.3 Luminosity Limits

To interpret the count-rate limits derived in the previous sections, we need a model for the X-ray spectrum of the RRATs, as well as the distance and interstellar absorption along each line of sight. For RRAT J0847–4316 we take the distance of $3.4 \pm 1$ kpc based on the observed dispersion measure and the Cordes & Lazio (2002) electron density model. Using the 3-dimensional Galactic extinction model of Drimmel, Cabrera-Lavers & López-Corredoira (2003), we find an optical extinction of $A_V \approx 3$ mag. This translates to a hydrogen column density of $N_H = 5 \times 10^{21}$ cm$^{-2}$ (based on Predehl & Schmitt 1999). This is similar to the value of $9 \times 10^{21}$ cm$^{-2}$ based on the observed dispersion measure of 293 pc cm$^{-1}$ assumed and 10% per cent ionisation (similar to the $N_H/DM$ ratio of RRAT J1819–1458), or the same value from the Dickey & Lockman (1990) H I data-set (likely to be an upper limit, since it is integrated through the Galaxy). Overall, values of $(5-10) \times 10^{21}$ cm$^{-2}$ seem likely, but the uncertainty is large given the poorly known distance.

For RRAT J1846–0257, we use a distance of $5.2_{-1.5}^{+2}$ kpc estimated from the dispersion measure. The Drimmel et al. (2003) model gives an extinction of $A_V \approx 9$ mag which implies $N_H = 1.6 \times 10^{22}$ cm$^{-2}$. We compare this with the DM-derived value of $0.7 \times 10^{22}$ cm$^{-2}$ or the H I-derived value of $2 \times 10^{22}$ cm$^{-2}$. We also have the value of $4 \times 10^{22}$ cm$^{-2}$ measured for PSR J1846–0258/Kes 75, which is likely at a comparable or slightly larger distance ($5.1-7.5$ kpc; Leahy & Tian 2008) as RRAT J1846–0257. This gives us a wide range to consider, $(1-4) \times 10^{22}$ cm$^{-2}$, again with the understanding that the large uncertainty on the distance gives an additional contribution.

As an aside, we consider the possibility that PSR J1846–0258 and RRAT J1846–0257 were members of a binary system that was disrupted by a supernova. At 5 kpc their transverse separation of 2.5 arcmin is 3.6 pc. In this scenario, the explosion that produced RRAT J1846–0257 0.4 Myr ago ejected the progenitor of PSR J1846–0258, which would have been moving at a transverse velocity of $\sim 9$ km s$^{-1}$ before the second supernova explosion that created the Kes 75 remnant. This velocity is actually very low for an object ejected out of a binary, which typically move at several hundred km s$^{-1}$ (e.g., Wlemming et al. 2004), although we do not know the radial velocity of either object. Waiting $\sim 0.5$ Myr for the second supernova seems plausible, at least based on some studies of binary evolution (Brown 1993). If PSR J1846–0258 were actually the second supernova of the system it could have interesting implications, as the progenitors of magnetars are typically thought of as quite massive (e.g., Klose et al. 2004; Eikenberry et al. 2004; Gaensler et al. 2003; Muno et al. 2003) and PSR J1846–0258 shares some (but not all) characteristics of magnetars (Gavriil et al. 2008), but being the second supernova would suggest it is less massive than its companion. Mass transfer or interactions during binary evolution could likely resolve the discrepancy.

We determine luminosity limits in two ways. First, we assume that the entire surface of the RRATs emits as a blackbody, and we use our count-rate limits to set upper limits to the surface temperature (measured at infinity, like all blackbody parameters discussed below). Blackbody emission is not necessarily the best assumption as many other atmosphere models are more realistic (e.g., Reynolds et al. 2006) and found hydrogen atmospheres gave acceptable fits for RRAT J1819–1458), but we keep it for simplicity. In Figure 2 we give temperature limits both for a canonical 10 km neutron star radius and a 20 km radius more similar to that inferred for RRAT J1819–1458 (Reynolds et al. 2006), covering the wide range in $N_H$ possible for each source. [The larger radius is not likely physical, and may reflect a combination of errors in the distance or unrealistic models for the surface emission. However, more realistic models (e.g., model atmospheres) typically have larger areas than black-bodies.] As an alternate method, since assuming a constant emission area is not always consistent with observations of strongly pulsed neutron stars, we take the thermal spectrum measured for RRAT J1819–1458: a blackbody with $kT = 140$ eV and unabsorbed luminosity $4 \times 10^{34}$ erg s$^{-1}$ (McLaughlin et al. 2007). Again considering the wide range in $N_H$ possible for each source, we plot the limits on the unabsorbed thermal luminosity in Figure 2 for three blackbody temperatures: the nominal value 140 eV, and ±50 per cent of that value. The main goal of the range in temperature is to show the effects of interstellar absorption and the limited energy window of Chandra on the luminosity limits, although we physically motivate them in Section 3.

Assuming blackbody emission from a 20 km radius and the nominal absorption, the effective temperature limit on RRAT J0847–4316 is 77 eV (using $N_H = 5 \times 10^{21}$ cm$^{-2}$). While the count-rate limit is tighter for RRAT J1846–0257, the higher likely distance and absorption (although the DM is lower) mean that the limit is comparable, 91 eV (for $N_H = 2 \times 10^{22}$ cm$^{-2}$). Alternately, if we take blackbody emission at a fixed temperature of 140 eV we get luminosity limits of $1 \times 10^{33} d^2_4$ erg s$^{-1}$ and $3 \times 10^{32} d^2_{12}$ erg s$^{-1}$. The temperature limits for both sources are considerably cooler than for RRAT J1819–1458 for almost all absorptions values. Similarly, The luminosity limits for both sources are typically below that of RRAT J1819–1458 for a range of in-
put spectra, often by several orders of magnitude. Only for
the lowest temperature considered (70 eV) and absorptions
at the high end of the considered range do our limits become
less constraining, although we must consider the correla-
tion between distance and $N_H$, where a larger true distance
would also be associated with more absorption and hence
an even weaker limit. We also consider a non-thermal spec-
trum (power-law with photon index of 2), which gives limits
of $4 \times 10^{31} d_{154}^2 \mathrm{erg} \, \mathrm{s}^{-1}$ and $8 \times 10^{30} d_{154}^2 \mathrm{erg} \, \mathrm{s}^{-1}$ for J0847$-$4316
and J1846$-$0257.

3 DISCUSSION AND CONCLUSIONS

The X-ray emission from RRAT J1819$-$1458 was assumed
to be largely due to cooling emission from the neutron
star surface (Reynolds et al. 2006; McLaughlin et al. 2007),
with only a small contribution from an extended nebula
(Rea et al. 2004). If we expect similar emission from
RRATs J0847$-$4316 and J1846$-$0257, it would be dimin-
ished due to their older ages (characteristic ages of 0.8 and
0.4 Myr respectively, vs. 0.1 Myr for RRAT J1819$-$1458).
In the neutrino-dominated cooling regime, the tempera-
ture declines slowly with time, with surface temperature
$\sim t^{1/2}$ (Page et al. 2004). The transition to photon-
dominated cooling typically occurs around 0.1$-$1.0 Myr, and
after that the decline is much steeper and dependent on the
nature of the envelope, but exponents of 1$-$3 are common.
So in the worst case, and assuming that characteristic age
is correlated with true age (something that is not neces-
sarily true; e.g., Gaensler & Frail 2000; Kramer et al. 2003;
Kilian & van Kerkwijk 2008), we would expect tiny tem-
peratures < 10 eV for RRATs J0847$-$4316 and J1846$-$0257
that would be undetectable. However, we know of other neu-
tron stars with similar characteristic ages with luminosities
of $\sim 10^{33} \mathrm{erg} \, \mathrm{s}^{-1}$ (e.g., PSR B1055$-$52 with characteristic
age 0.5 Myr; De Luca et al. 2003). We also know that char-
acteristic age (and even true age) do not always correlate
strictly with effective temperature (van Kerkwijk & Kaplan
2008). So while it is tempting to say that the RRATs stud-
hed here are older and colder than RRAT J1819$-$1458, that
may be misleading. While the unknown distance and col-
umn densities limit the strength of any conclusions, our data
may actually provide upper limits on the luminosities of two
sources that point to a range in X-ray emission among the
RRATs.

The RRATs lie close to the INS in the $P$-$\dot{P}$ plane in
a region with few other pulsars, and appear like the INS to
have preferentially long periods (although there are substan-
tial selection effects; Deneva et al. 2009; McLaughlin et al.
2009). Our X-ray non-detections of the RRATs are actu-
ally consistent over most of the range in $N_H$ with emis-
ion like that seen from the INS: blackbodies with $kT =
40$ $-$ 100 eV and luminosities $\sim 10^{33} \mathrm{erg} \, \mathrm{s}^{-1}$. They are
generally consistent with a cooling sequence that also includes
the younger pulsars like PSR B0656+14 and PSR B1055$-$52
(Page et al. 2009), although the details of the emission are
difficult and there could be a small contribution from mag-
netic field decay (Kilian & van Kerkwijk 2009, and see be-
low). While the characteristic ages of the INS are a fac-
tor of 4$-$8 older than those of the RRATs considered here,
the true ages are likely comparable (Motch et al. 2005; Kaplan, van Kerkwijk & Anderson 2002, 2007). If the
RRATs and the INS were drawn from a single cooling se-
quence that evolved with the characteristic age, we would
expect J0847$-$4316 and J1846$-$0257 to lie somewhere be-
tween 140 eV (J1819$-$1458) and 70 eV (the mean of the
INS), with the luminosity declining accordingly. In that case
the RRATs could be at $\sim 10^{32} \mathrm{erg} \, \mathrm{s}^{-1}$ for much of the con-
sidered range in $N_H$, and significantly deeper observations
would be required to understand the true nature of their emission.
Considering true age rather than characteristic age complicates the situation as the RRATs do not have any
such measurements, but the general argument still holds.

The X-ray luminosity of RRAT J1819$-$1458 is above
the spin-down luminosity $\dot{E}$ ($\sim 3 \times 10^{32} \mathrm{erg} \, \mathrm{s}^{-1}$), im-
plying that rotationally-powered non-thermal processes do not
drive the X-ray emission, contrary to what is seen for many
rotation-powered pulsars ($L_X \sim 10^{-3} \dot{E}$) (Becker & Trumper
1997; Possenti et al. 2002; Cheng et al. 2006) but consistent with the INS. The non-thermal contributions to the X-ray
emission from RRATs J0847$-$4316 and J1846$-$0257 would be
$10^{28}$$-$29 erg s$^{-1}$, below our limits even for optimistic val-
ues of the distance and $N_H$. Therefore our limits cannot
really constrain the expected level of non-thermal emission
from these sources. We note, though, that the observed spin-
down luminosity appears too low to power the extended
X-ray emission observed around RRAT J1819$-$1458 (inter-
preting it as a pulsar wind nebula) requiring some other
energy source (Rea et al. 2009), which is also a possible con-
clusion about the nebula around the INS RX J1856.5$-$3754
(van Kerkwijk & Kaplan 2008).

A final possibility for the emission of
RRAT J1819$-$1458 is that, while the spectrum is thermal, the emission we see is cooling augmented by magnetic field
decay (e.g., Heyl & Kulkarni 1998; Pons et al. 2009, and
references therein). While the exact field decay mechanisms
and timescales are still uncertain (Goldreich & Reisenegger
1992), field decay may be relevant for objects of ages
< 1 Myr and magnetic fields > 2 $\times 10^{11}$ G (Pons et al.
2004), which is the correct range for the RRATs considered
here. We would expect generally that for objects of similar
ages (such that the same decay mechanisms are operating)
the luminosity due to field decay would scale as $B |B|$
(Heyl & Kulkarni 1998), where $|B|$ $\sim B/\tau_B$ and \tau_B
is the relevant decay timescale which may itself depend on $B$
(Heyl & Hernquist 1997). There are many complexities and
dependencies (magnetic field configuration, temperature
effects, etc.) that we must ignore here, but if the heating is
due to Ohmic diffusion (Pons et al. 2009) then the timescale
is independent of $B$ and the luminosity should scale as $B^2$.
So the factor of ~ 2 difference in dipolar magnetic field
between RRAT J1819$-$1458 and the others would lead to
at most a factor of 4 difference in instantaneous thermal
luminosity. Once again, this is consistent with our limits
but the large uncertainties in the distances and absorptions
make conclusions difficult. Additionally, this energy takes
time to diffuse to the surface, so the flux we see now may
represent a different set of conditions in the past when the
difference in magnetic field was even wider, if decay makes
the field strength converge to a single value as discussed by
Pons et al. 2009.

In summary, deep Chandra searches at the positions of
RRATs J0847$-$4316 and J1846$-$0257 show no X-ray emis-


of X-ray sources in our Chandra images. We assume a radius of 10 km (dashed lines) or 20 km (solid lines). We take a range of interstellar absorption $N_H$, where the arrows show the estimates of $N_H$ from various methods as labelled: the extinction model of Drimmel et al. (2003) as “$A_V$”, the RRATs dispersion measure as “DM”, Galactic H I data of Dickey & Lockman (1990) as “HI”, and the PSR J1846–0258/Kes 75 complex as “SNR.” Values for RRAT J1819–1458 are on the top, values for RRAT J1846–0257 are on the bottom, and the intersections with the luminosity limits are marked with circles and squares, respectively. The dotted line shows the effective temperature of RRAT J1819–1458.

**Figure 2.** Left: Upper limits to the blackbody effective temperatures at 3σ confidence for RRAT J0847–4316 (thick blue lines) at an assumed distance of 3.4 kpc, and RRAT J1846–0257 (thin red lines) at an assumed distance of 5.2 kpc, given the non-detection of X-ray sources in our Chandra images. We assume a radius of 10 km (dashed lines) or 20 km (solid lines). We take a range of interstellar absorption $N_H$, where the arrows show the estimates of $N_H$ from various methods as labelled: the extinction model of Drimmel et al. (2003) as “$A_V$”, the RRATs dispersion measure as “DM”, Galactic H I data of Dickey & Lockman (1990) as “HI”, and the PSR J1846–0258/Kes 75 complex as “SNR.” Values for RRAT J1819–1458 are on the top, values for RRAT J1846–0257 are on the bottom, and the intersections with the luminosity limits are marked with circles and squares, respectively. The dotted line shows the effective temperature of RRAT J1819–1458. Right: Upper limits to the unabsorbed X-ray luminosities at 3σ confidence in the 0.3–8 keV range for RRAT J0847–4316 (thick blue lines) at an assumed distance of 3.4 kpc, and RRAT J1846–0257 (thin red lines) at an assumed distance of 5.2 kpc. We assume a blackbody model with temperature of 70 eV (solid line), 140 eV (dashed line), or 210 eV (dot-dashed line) for a range of interstellar absorption $N_H$. The dotted line shows the luminosity of RRAT J1819–1458 (4 × 10$^{33}$ erg s$^{-1}$). The arrows and filled symbols are the same as in the left panel.

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REFERENCES

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