Chandra Smells a RRAT

X-ray Detection of a Rotating Radio Transient

1 Introduction

Astronomers are still coming to terms with the fact that the zoo of isolated neutron stars harbours an increasingly diverse population. Objects of considerable interest include radio pulsars, anomalous X-ray pulsars, soft gamma repeaters, central compact objects in supernova remnants (SNRs), and dim isolated neutron stars. A startling new discovery has now forced us to further expand this group, McLaughlin et al. (2006) have recently reported the detection of eleven “Rotation RAdio Transients”, or “RRATs”, characterised by repeated, irregular radio bursts, with burst durations of 2–30 ms, and intervals between bursts of ∼ 4 min to ∼ 3 hr. The RRATs are concentrated at low Galactic latitudes, with distances implied by their dispersion measures of ∼ 2–7 kpc.

For ten of the eleven RRATs discovered by McLaughlin et al. (2006), an analysis of the spacings between repeat bursts reveals an underlying spin period, \( P \), and also in three cases, a spin period derivative, \( \dot{P} \). The observed periods fall in the range 0.4 s < \( P < 7 \) s, which generally overlap with those seen for the radio pulsar population.

For the three RRATs with values measured for both \( P \) and \( \dot{P} \), a characteristic age, \( \tau_c \), and a dipole surface magnetic field, \( B \), can both be inferred, as listed in Table 1. These sources can also be placed on the standard \( P – \dot{P} \) diagram, and can thus be compared to other populations of rotating neutron star:

- RRAT J1317–5759 has properties typical of radio pulsars, except for a relatively long spin period.
- RRAT J1819–1458 is very young, with a high magnetic field. On the \( P – \dot{P} \) diagram, it is located in the upper-right region, in the same area occupied by the magnetars and by the high-field radio pulsars.
- RRAT J1913+3333 has spin properties indistinguishable from the bulk of radio pulsars.

We here present the X-ray detection of RRAT J1819–1458, which provides a further point of comparison with the various neutron star population. The details of this...
detection and its interpretation are discussed by Reynolds et al. (2006).

Table 1 Properties of the three RRATs with measured period derivatives.

| Source          | P (sec) | $\tau_c$ (Myr) | $B \left(10^{12} \, G\right)$ |
|-----------------|---------|-----------------|-------------------------------|
| RRAT J1317–5759 | 2.6     | 3.3             | 5.83                          |
| RRAT J1819–1458 | 4.3     | 0.12            | 50                            |
| RRAT J1913+3333 | 0.92    | 1.9             | 2.7                           |

2 X-ray Emission from RRAT J1819–1458

2.1 Detection

As mentioned above, RRAT J1819–1458 is very young, and has a high surface magnetic field. This source bursts every $\sim 3$ min, making it the most active of the known RRATs. Its dispersion measure of $196 \pm 3$ pc cm$^{-3}$ corresponds to an estimated distance of 3.6 kpc, with considerable uncertainty.

RRAT J1819–1458 sits only $\sim 11'$ from the young SNR G15.9+0.2. This source was the target of a 30 ks observation with Chandra ACIS in May 2005, and RRAT J1819–1458 fortuitously falls within the field of view (Reynolds et al., 2006). As shown in Figure 1, there is a clear detection of a bright, unresolved X-ray source within the error ellipse for RRAT J1819–1458. Using the X-ray differential source count distribution for the Galactic plane of Sugizaki et al. (2001), we find that the probability of finding a field source of this count rate at this position is $< 10^{-4}$, and conclude that we have both identified and localised the X-ray counterpart of RRAT J1819–1458.

2.2 Spectrum and Variability

We have extracted $524 \pm 24$ counts from the X-ray counterpart to RRAT J1819–1458, the spectrum from which is shown in Figure 2. While this is insufficient for detailed spectral modelling, it still yields crucial information.

Fitting simple absorbed power-law and blackbody models, we find that the spectrum is a poor fit to the former, but a good fit to the latter (Reynolds et al. 2006). At a distance of $3.6d_{\text{c,6}}$ kpc, the inferred blackbody radius (as viewed at infinity) is $20d_{\text{c,6}}$ km, which is consistent with standard neutron star equations of state, given the uncertainty in the distance estimate. For this blackbody fit, the foreground absorbing column is $N_H = 7.4^{-1}_{-1} \times 10^{21}$ cm$^{-2}$, and the surface temperature (at infinity) is $kT_{\infty} = 120 \pm 40$ eV. In the energy range 0.5–8.0 keV, the unabsorbed flux is $2 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ and the isotropic luminosity is $3.6d_{\text{c,6}}^2 \times 10^{33}$ ergs s$^{-1}$.

Given the extreme variability of the source seen at radio wavelengths, it is of interest to quantify the level of X-ray variability seen in this observation. Examination of individual CCD frames (at a time-resolution of 3.2-seconds) shows no evidence for individual brief X-ray bursts that might be a counterpart to the RRAT phenomenon, with a 3-$\sigma$ upper limit on the observed fluence of any burst of $3 \times 10^{-11}$ ergs cm$^{-2}$ in the 0.5–8 keV energy range. The data also show no evidence of variability on any time-scale ranging from 3.2 s to 5 days (the time-span covered by the observations). Although the time resolution is only slightly shorter than the spin period,
3 Comparison with Other Sources

It is unclear whether the RRATs are a completely new group of neutron stars, or are a new manifestation of one of the previously known classes of object. Since all classes of young neutron star are X-ray emitters, the detection reported here provides vital new information which allows us to begin to discriminate between various interpretations for the RRATs.

We first note that while many neutron stars are pulsed in X-rays, those which produce thermal emission inevitably exhibit low pulsed fractions, due to gravitational bending of the light emanating from their surfaces (e.g., \textit{Psaltis et al.} 2000). Thus our relatively poor limit on pulsed fraction is unsurprising and unconstraining.

Despite its location near the magnetars on the \( P - \dot{P} \) diagram, the X-ray properties of RRAT J1819–1458 are distinct from those seen for magnetars: the RRAT is much colder and less luminous than the magnetars, and apparently lacks the hard X-ray tail seen for these sources, at our current level of sensitivity. Furthermore, the magnetar birth rate is well below that estimated for the RRAT population \textit{(Popov et al.} 2006). The only possible link to magnetars is with the transient magnetar XTE J1810–197 which, while in quiescence, had a surface temperature \( kT_{\infty} \approx 150 - 180 \) eV \textit{(Ibrahim et al.} 2004; \textit{Gotthelf et al.} 2004), comparable to that seen here.

The X-ray temperature of RRAT J1819–1458 is also well below those of the “central compact objects”, while its temperature and luminosity are above those of most of the dim isolated neutron stars.

The one population whose X-ray properties provide a reasonable match to that of the RRAT is that of radio pulsars, for which sources with ages around 100 kyr show spectra very similar to what we have found here. For example, PSR J0538+2817 is 30 kyr old and has \( kT_{\infty} = 160 \) eV, while PSR B0656+14 is 110 kyr old and has \( kT_{\infty} = 70 \) eV (see \textit{Reynolds et al.} 2006, for details). The X-ray emission from RRAT J1819–1458 thus suggests that this source is a normal radio pulsar, albeit one that produces unusual radio bursts. Additional evidence to support this possibility is the subsequent discovery from PSR B0656+14 of RRAT-like behaviour \textit{(Weltevrede et al.} 2006). If PSR B0656+14 was placed at the distance of RRAT J1819–1458, its occasional bright radio bursts would still be seen, but not the underlying regular train of pulsations.

One point to note is that the inferred surface magnetic field strength of RRAT J1819–1458 is more than an order of magnitude greater than that of PSRs J0538+2817 and B0656+14 discussed above. Two radio pulsars with comparable magnetic fields that have been detected in X-rays are PSRs J1718–3718 \textit{(Kaspi and McLaughlin} 2003\) and J1119–6127 \textit{(Gonzalez et al.} 2005). These sources show temperatures \((kT \sim 150 - 200 \) eV\) and luminosities \((\sim 10^{32} - 10^{33} \) ergs s\(^{-1}\)) comparable to that of RRAT J1819–1458, although both sources are probably much younger.
(35 and 1.7 kyr, respectively) and, in contrast to RRAT J1819–1456, have X-ray luminosities less than their spin-down luminosities.

4 Possible Interpretations

If the RRATs are normal radio pulsars as proposed above, we then need to explain their transient behaviour. One possibility, discussed by Zhang et al. (2000), is that RRATs are pulsars that are no longer active, but for which a temporary “star spot” with multipole field components emerges above the surface. This magnetic field component could temporarily reactivate the radio beaming mechanism, producing the observed bursts.

The difficulty with this possibility is that none of the RRATs with known values of $P$ appear to be near the “death line” in the $P$ – $P$ diagram, beyond which the pulsar mechanism is expected to turn off. To account for this, Zhang et al. (2000) have proposed that RRATs have dipole fields offset from their centres, causing their magnetic fields to be over-estimated. However, the X-ray temperature seen for RRAT J1819–1458 is consistent with it being a ~100-kyr old neutron star (see Sec. 3 above), in reasonable agreement with its characteristic age as listed in Table I and confirming that if this is a radio pulsar, it is as yet nowhere near death.

Zhang et al. (2000) also consider the possibility that RRATs are caused by a brief reversal of the direction in which radio beams are emitted. They draw upon the previous work of Gil et al. (1994), who showed that whenever PSR B1822–09 produces “nulls” in its main pulse, it produces a much weaker interpulse, which has been interpreted by Dvks et al. (2005) to correspond to radiation temporarily emitted in the opposite direction. If one invokes an emitting geometry in which the main pulse is never seen, then the interpulse alone, appearing only when the unseen main pulse nulls, might correspond to RRAT-like emission. The difficulty with this interpretation is that in PSR B1822–09 this reversal lasts for several minutes, in contrast to the RRATs, for which multiple bursts in succession are yet to be observed.

Finally, the RRAT mechanism might be produced by interaction of the neutron star with an equatorial fallback disk or with orbiting circumpolar debris. Accretion from a disk should usually quench the radio emission mechanism, but sporadic drops in the accretion rate could allow the radio beam to turn on for a fraction of a second, producing the RRAT phenomenon (Lewandowski et al., 2004). This possibility is at odds with the behaviour seen by Weltevrede et al. (2000) for PSR B0656+14, in which the RRAT-like bursts are superimposed on an underlying persistent series of faint radio pulsations. Alternatively, episodic injection of material from a circumpolar asteroid belt could temporarily activate a quiescent region of the magnetosphere, producing a RRAT burst, in some cases from a radio pulsar that is normally beaming away from us (Cordes and Shannon, 2006).

5 Future Observations and Conclusions

A variety of forthcoming observations should be able to cast more light on the possibilities discussed above, and on the spatial and spin distributions of these sources. Several groups have already undertaken new radio searches for RRAT-like emission from other classes of neutron stars. Near-infrared observations with the VLT have also been obtained for some RRATs, to provide stronger constraints on the X-ray to infrared flux ratio of these sources, and to look for hints of a fossil / fallback disk (Wang et al., 2006). Meanwhile, in a project called “Astro Pulse”, the data from the Arecibo SETI@Home project are being re-analysed for short transient signals. With the sensitivity of Arecibo, many RRATs may be found in this analysis.

Finally, following on from our X-ray detection discussed here, XMM-Newton observations of two RRATs have been approved for Cycle 5; of RRAT J1819–1458 (to obtain a better spectrum and to properly search for pulsations) and of RRAT J1317–5759 (to see if it too emits detectable X-rays).

A final point to make is that it is already clear from the 11 RRATs known that the birth rate of these objects is ~3 – 4 times that previously estimated for all radio pulsars (McLaughlin et al., 2005; Popov et al., 2006). We are thus only seeing the upper tip of a large transient distribution. When one combines this with the populations of nullers (Backer, 1970), “bursters” (e.g., PSR J1752+2359; Lewandowski et al., 2004), “winkers” (PSR B1931+24; Kramer et al., 2000) and “burpers” (GCRT J1745–3009; Hyman et al., 2005), it becomes clear that a full study of the transient radio sky is needed (Cordes et al., 2004). The next generation of radio telescopes, with the capability of monitoring very wide fields of view (e.g., LOFAR, xNTD and the SKA) should make many further discoveries of such phenomena.

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