A Deep Search for Pulsations from the Nearby Isolated Neutron Star
RX J1856.5−3754
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ABSTRACT

We present the results of a deep search for pulsations from the nearby isolated neutron star RX J1856.5−3754 using the 450 ks Director’s Discretionary Time (DDT) Chandra LETG/HRC-S observation completed on 2001 Oct 15. No pulsations were detected. We find a 99% confidence upper limit on the pulsed fraction of $\sim 4.4\%$ for worst-case sinusoidal pulsations with frequency $\lesssim 50 \text{ Hz}$ and frequency derivatives $-5 \times 10^{-10} \lesssim \dot{f} \lesssim 0 \text{ Hz s}^{-1}$. This lack of detection is consistent with a neutron star with $R \approx 6 \text{ km}$ and $M \approx 1 \text{ M}_\odot$ at a distance $\sim 60 \text{ pc}$, as determined by Pons et al. (2002). The strong gravitational field of such a star sufficiently deflects X-ray emission from the emitting regions so as to prevent significant modulation of the signal.

Subject headings: stars: individual (RX J1856.5−3754) — stars: neutron — X-rays: stars

1. Introduction

The ROSAT observatory provided us with at least six soft X-ray emitting point sources which are likely to be radio-quiet isolated neutron stars (NSs) emitting thermally (\textit{for a review see})\textsuperscript{mot02}. The nearest of these systems is RX J1856.5−3754 (hereafter RXJ1856), which was first observed as an unidentified point source in the EINSTEIN Slew Survey (Elvis et al. 1992) and later identified as an isolated NS by Walter et al. (1996). Subsequent observations in the optical and ultraviolet (UV) have strengthened this claim by detecting a faint blue optical counterpart (Walter & Matthews 1997), measuring its proper motion (Walter 2001), and identifying a bow-shock $H_\alpha$ nebula around the NS (van Kerkwijk & Kulkarni 2001). Walter (2001) also used Hubble Space Telescope (HST) data to measure a parallax distance of $\sim 61 \text{ pc}$ to RXJ1856. However, Kaplan et al. (2002) have recently re-analyzed the same data and determined a distance of $\sim 140 \text{ pc}$ — the reasons for the large discrepancy are, as of yet, unclear.

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Despite these measurements, the nature of RXJ1856 remains a mystery. Is it young or old? Is it an ordinary radio pulsar beaming away from us, a low magnetic field neutron star accreting from the interstellar medium, or a high-field “magnetar”? The key to answering these questions lies in detecting pulsations from this source, from which we could then determine its spin-period, age, braking torque and magnetic field strength. Even a non-detection of pulsations can provide useful constraints on the mass, radius, and emitting geometry of the NS.

On 2000 March 10, the Chandra X-Ray Observatory observed RXJ1856 for $\sim 56$ ks using the Low Energy Transmission Grating Spectograph (LETGS, \text{"bgk+00.\text{" The LETGS is composed of the High Resolution Camera Spectroscopy (HRC-S, \text{"mck+98 and the Low Energy Transmission Grating (LETG). If an isolated neutron star is sufficiently magnetized, the resulting anisotropies in the temperature distribution of the crust can produce hotspots of X-ray emission on the surface of the star.

If the magnetic axis is mis-aligned with the rotation axis, these hotspots can potentially produce a periodic modulation of the soft X-ray intensity at the rotation period of the NS. Searches for these pulsations using the Chandra data were carried out by Burwitz et al. (2001) who placed an upper limit on the pulsed fraction (for frequencies $\lesssim 40$ Hz) of $\sim 8\%$. Similar searches have been undertaken with archival ROSAT and ASCA data by Pons et al. (2002) who placed a 50\% confidence limit on the pulsed fraction of $\sim 6\%$. It should be noted that three other radio quiet isolated NS candidates have been reported to show X-ray pulsations: RX J0720.4$-3125$ with a period of 8.4 s and a pulsed fraction of $\sim 12\%$ (Haberl et al. 1997), RX J0420.0$-5022$ with a period of 22.7 s and a pulsed fraction of $\sim 40\%$ (Haberl et al. 1999), and RBS 1223 with a period of 5.16 s and a pulsed fraction of $\sim 20\%$ (Hambaryan et al. 2002).

In 2001 October, RXJ1856 was observed with the Chandra LETGS for an additional 450 ks of Director’s Discretionary Time (DDT) over the course of $\sim 7.25$ days. The purpose of the observation was to search for features in the spectrum — due to heavy elements in the NS atmosphere, in particular — in order to constrain the NS equation of state. However, these data are of sufficient time resolution to allow a deep search for pulsations as well. The data were made public soon after the observation was completed. We conducted brute-force period folding and advanced Fourier analyses of this data in order to try to identify the spin parameters of the neutron star. In addition, we have analyzed archival observations of RXJ1856 from both ROSAT and Chandra in order to specify a consistent set of upper limits to the pulsed fraction.

### 2. Observations and Data Preparation

The DDT observation comprised ObsIds 3382, 3380, 3381, and 3399 in chronological order beginning on 2001 October 8 and ending on 2001 October 15 (see Table 1) and were taken in the standard LETGS configuration. The total exposure time was 450 ks with significant gaps between the various ObsIds giving a total duration of $\sim 626$ ks.
The data were prepared in a very simple manner. We extracted all events from within \( \sim 2'' \) of the centroid of the zero-order image from each ObsId. The arrival times of these events were transformed to the Solar System Barycenter using the standard *Chandra Interactive Analysis of Observations (CIAO, v2.2)* tool `axBary`, the nominal position of RXJ1856 from Walter (2001) of RA(J2000) = 18\(^{h}\) 56\(^{m}\) 35.5 and DEC(J2000) = −37° 54′ 36.8′′, and the preliminary Level 2 orbital ephemeris file distributed with the data release. We binned the 90134 resulting events into 1.5 ms time bins to create a 420 million point time series that was used in the coherent Fourier analysis described in §3.1.

A wiring error in the HRC causes each event to be tagged with the arrival time of the previous event. Unfortunately not every event is telemetered to the ground, so the arrival times of recorded events are typically in error by a few ms\(^4\). In order to improve the accuracy of these arrival times and to restrict the number of counts in order to make a brute-force period folding search computationally feasible, we reprocessed the data using the time filtering scheme described by Tennant et al. (2001). By shifting all arrival times in the Level 1 event files back to the previous event, filtering the data spatially, barycentering, and then keeping only those events that arrived within 1 ms of the previous event, we are guaranteed of having much more accurate arrival times (\( \lesssim 1 \) ms) but at the cost of a loss of \( \sim 95\% \) of the events (see Table 1).

In order to verify preparation methods for the data, we processed events from the LETGS observation of the Crab pulsar (ObsId 759) in the same manner as described above. The Crab pulsar was easily detected in the data at the expected barycentric rotation period and with the expected pulse profile given the HRC wiring error.

### 3. Data Analysis

In order to maximize our sensitivity to coherent pulsations with a variety of pulse shapes, we searched the data using two very different techniques. For maximum sensitivity to sinusoidal pulse profiles, we performed a coherent Fourier analysis of the complete DDT observation. For better sensitivity to more complicated pulse profiles, we performed period folding searches with the significance of each trial determined by the Bayesian method developed by Gregory & Loredo (1992, 1996).

#### 3.1. Fourier Analysis

We Fast Fourier Transformed the 420 million point time series described in §2 and searched the resulting Fourier amplitudes using an advanced pulsar search code. The search included harmonic

\( ^4 \text{See http://asc.harvard.edu/cal/Links/Hrc/CIP/timing.html} \)
summing to improve sensitivity to low duty-cycle pulsations, Fourier interpolation to minimize the effects of “scalloping” (van der Klis 1989), and the ability to compensate for signals with a constant frequency derivative (i.e. an “acceleration” search) by matched filtering of the complex Fourier amplitudes with a series of template responses (Ransom et al. 2001; Ransom 2001).

Due to the limitations in the HRC-S time resolution, we limited our search to frequencies $f < 100 \text{ Hz}$. Similarly, we restricted the range of acceptable frequency derivatives to be from $-5 \times 10^{-10} \leq \dot{f} \leq 0 \text{ Hz s}^{-1}$, which encompasses all known isolated pulsars. As an example of a near worst-case scenario which requires the use of acceleration searches, it is useful to note that the Crab pulsar (i.e. $f = 29.82 \text{ Hz}$ and $\dot{f} = -3.7 \times 10^{-10} \text{ Hz s}^{-1}$) would drift by $|\dot{f}T^2| \sim 149$ Fourier bins during the observation, where $T$ is the total duration of the data. In an uncorrected power spectrum such a signal would be smeared below detectability. After accounting for the number of independent trials searched, no candidates were detected with an equivalent Gaussian significance of greater than $2\sigma$. For completeness, we also searched for signals with positive frequency derivative from $0 \leq \dot{f} \leq 5 \times 10^{-10} \text{ Hz s}^{-1}$ with no result.

In addition to searching the Chandra DDT observation, we searched the archival LETGS observation (ObsId 113, $\sim 55 \text{ ks}$) of RXJ1856 as well as the 1997 October 9 ROSAT High Resolution Imager (HRI) observation ($\sim 29 \text{ ks}$) of RXJ1856 using virtually identical techniques. Not surprisingly, no candidates were found with significance greater than $2\sigma$ in either case. In addition, none of the lower significance candidates from these searches matched any of the low-significance candidates from the DDT observation.

### 3.2. Period Folding Analysis

We conducted brute-force period folding of the time-filtered events from each of the individual observations using a modified version of the Gregory & Loredo (1992) technique that allows searching over $\dot{f}$ as well as $f$. This method maintains sensitivity to a wide variety of pulsed signals by matching the complexity of a signal’s pulse shape with an appropriate number of bins in the folded profile aligned at the appropriate phase.

Each individual observation was searched using the time-filtered events described in §2 over a range of frequencies from $0.001 < f < 100 \text{ Hz}$ and frequency derivatives from $-5 \times 10^{-10} \leq \dot{f} \leq 0 \text{ Hz s}^{-1}$. The candidate lists from each observation were then compared to those from each of the other observations to find likely matches in $f$ and $\dot{f}$. No interesting candidates were found.

We also searched the two longest observations (ObsIds 3380 and 3381) together using a hierarchical method in order to improve our sensitivity to weaker signals. The number of operations required for a folding search that includes $\dot{f}$ goes as $\sim N_{\text{phot}}T^2$, where $N_{\text{phot}}$ is the total number of photons and $T$ is the total duration of the observation ($N_{\text{phot}} = 3582$ and $T = 395 \text{ ks}$ for these two observations together). We first searched ObsId 3380 ($N_{\text{phot}} = 1743$, $T = 167.5 \text{ ks}$), which took an order of magnitude less time than that required to search both ObsIds together, and identified
candidates above a very low threshold around which to search both ObsIds together. While such a technique can save a very large amount of CPU time, some sensitivity is obviously sacrificed. This portion of the search required over 1000 CPU-hours on a cluster of modern workstations and produced no significant candidates.

### 3.3. Pulsed Fraction Limits

Since no candidates were found in any part of our search, upper limits on the pulsed fraction of RXJ1856 can be derived based on the predicted response of a worst-case sinusoidal signal during the Fourier analysis. We define the pulsed fraction as the number of pulsed counts divided by the total number of counts from a source. Equivalently, assuming data described by

$$s(t) = a [1 + \sin(2\pi ft + \phi)] + b,$$

where $t$ is the time since the start of the observation, $\phi$ is the pulse phase, and $a$ and $b$ are the pulsed and unpulsed count rates, the pulsed fraction is given by $f_p = a/(a + b)$.

Noting the total number of counts in the data is $N_{\text{phot}} = (a + b)T$, the expectation value of the properly normalized power for this signal will be

$$\langle P \rangle = \frac{a^2T^2}{4N_{\text{phot}}} + 1 = \frac{a^2T}{4(a + b)} + 1,$$

where the addition of “1” represents the expectation value of the noise power in each Fourier bin (e.g., van89,vvw+94). Substituting and solving for the pulsed fraction gives

$$f_p = \sqrt{\frac{4\langle P \rangle - 1}{N_{\text{phot}}}}. \tag{3}$$

When no pulsation is detected during a search, an upper limit on the pulsed fraction that the data could still contain can be calculated at some level of confidence $C$, based on the maximum power found in the search. This power level must be adjusted, however, such that given a large number of equivalent observations, a real signal will exceed the measured maximum power a fraction $C$ of the time. The correct method for calculating this power is described in detail by Vaughan et al. (1994). These calculations are sensitive to how the data are binned and the number of independent trials searched — quantities that can be difficult to estimate. Once this power (which includes contributions from the signal as well as noise) has been calculated, substituting it for $\langle P \rangle - 1$ in eqn. 3 gives the upper limit on $f_p$ at a confidence level $C$.

Our best estimates for the limiting pulsed fraction for RXJ1856 based on the new Chandra observations, as well as the archival Chandra and ROSAT observations, are given in Table 2. Slightly different upper limits are quoted based on the fact that the number of trials is very different when comparing an acceleration search with a more standard un-accelerated Fourier analysis. For
the archival data sets, our 50% confidence upper limits for un-accelerated searches are roughly consistent with (but slightly more conservative) than the values reported in Burwitz et al. (2001) and Pons et al. (2002). For “normal” pulsars with relatively slow spin periods (i.e. \( f \lesssim 5 \) Hz and \( \dot{f} \lesssim 10^{-12} \) Hz s\(^{-1}\), the un-accelerated values are the most appropriate.

4. Discussion

Analysis of the X-ray, UV and optical emission from RXJ1856 suggests that its spectrum can be fit by a two-component blackbody: a 20-eV component seen at lower energies and corresponding to emission from the entire neutron star surface, and a 60-eV component seen in X-rays and representing smaller, hotter regions of emission (Burwitz et al. 2001; Pons et al. 2002). In this case, we expect to see X-ray pulsations at the star’s rotation period, resulting from the motion of these hotspots through our line-of-sight.

However, such pulsations can be difficult to detect, particularly when the effects of light deflection due to general relativity are taken into account. Psaltis et al. (2000) have recently made detailed calculations of the pulsed fraction expected to result from thermal hotspots on a spinning neutron star. The likelihood of detecting pulsations at a given pulsed fraction depends on the fractional surface area of the emitting region, \( \alpha \), the neutron star mass, \( M \), and its radius, \( R \). Based on the size of the emission region determined from spectral fits, Pons et al. (2002) suggest values in the range \( 0.2 < \alpha < 0.3 \), while the Chandra observations of March 2000 imply \( \alpha \lesssim 0.1 \) (Burwitz et al. 2001).

The 99% confidence upper limit of 4.4% determined here is by far the most constraining limit yet on the pulsed fraction of X-ray emission from RXJ1856. Assuming the range of fractional areas described above, Figure 6 of Psaltis et al. (2000) demonstrates that neutron stars with \( R/M \gtrsim 9 \) km/M\(_{\odot}\) should show pulsations above this limit for most orientations, while smaller and/or more massive stars cause sufficient gravitational deflection of the emission to reduce the pulsed fraction below this level. Pons et al. (2002) determine \( R/M \sim (6 - 7) \) km/M\(_{\odot}\), which is indeed in the range for which the amplitude of pulsations are expected to be below the sensitivity of the available data. Very recently, Kaplan et al. (2002) have re-derived the parallax of RXJ1856 and argue for a larger distance to the source which would imply \( R/M \sim 9 \) km/M\(_{\odot}\). There is a \( \sim 80\% \) probability that such a star would show pulsations with a pulsed fraction at the level \( > 4.4\% \) (Psaltis et al. 2000), making it harder to reconcile this larger distance with the interpretation of X-ray emission from thermally emitting hotspots on a rotating NS.

The inferred area for the X-ray emitting region is strongly dependent upon the presence and properties of any atmospheric component. Clearly, spectral analysis and modeling of the 2001-epoch Chandra data will be of great interest, both to better constrain the existence and extent of any hotspots, and to confirm the surprisingly small radius claimed for this source.
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REFERENCES


Table 1. *Chandra LETG/HRC-S* Observation Log

<table>
<thead>
<tr>
<th>ObsId</th>
<th>$T_{\text{START}}$ (MJD)</th>
<th>Exposure (ks)</th>
<th>Events (Raw)$^a$</th>
<th>Events (1 ms Filter)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>113</td>
<td>51613.33</td>
<td>55.5</td>
<td>10436</td>
<td>536</td>
</tr>
<tr>
<td>3382</td>
<td>52190.36</td>
<td>102.0</td>
<td>20072</td>
<td>1094</td>
</tr>
<tr>
<td>3380</td>
<td>52192.22</td>
<td>167.5</td>
<td>33703</td>
<td>1743</td>
</tr>
<tr>
<td>3381</td>
<td>52194.81</td>
<td>171.1</td>
<td>34571</td>
<td>1839</td>
</tr>
<tr>
<td>3399</td>
<td>52197.50</td>
<td>9.3</td>
<td>1788</td>
<td>104</td>
</tr>
</tbody>
</table>

$^a$These are the unfiltered events extracted from a $\sim 2''$ region around the nominal position of RXJ1856: RA(J2000) = 18$^h$ 56$^m$ 35.5$^s$, DEC(J2000) = $-37^d$ 54$^m$ 36.8$''$

$^b$These events were time-filtered such that their arrival times differed by no more than 1 ms from the event recorded after them (see §2).

Table 2. Pulsed Fraction Limits for RX J1856.5−3754

<table>
<thead>
<tr>
<th>ObsIds</th>
<th>$P_{\text{max}}$</th>
<th>$N_{\text{trials}}$</th>
<th>$f_p^{50%}$</th>
<th>$f_p^{99%}$</th>
<th>$P_{\text{max}}$</th>
<th>$N_{\text{trials}}$</th>
<th>$f_p^{50%}$</th>
<th>$f_p^{99%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400864$^a$</td>
<td>18.4</td>
<td>2.8</td>
<td>&lt; 6.8%</td>
<td>&lt; 9.6%</td>
<td>21.4</td>
<td>19</td>
<td>&lt; 7.4%</td>
<td>&lt; 10.2%</td>
</tr>
<tr>
<td>113$^b$</td>
<td>20.5</td>
<td>5.6</td>
<td>&lt; 9.1%</td>
<td>&lt; 12.7%</td>
<td>20.5</td>
<td>8.8</td>
<td>&lt; 9.1%</td>
<td>&lt; 12.7%</td>
</tr>
<tr>
<td>3380−2, 3399$^b$</td>
<td>21.0</td>
<td>45</td>
<td>&lt; 2.9%</td>
<td>&lt; 4.1%</td>
<td>26.0</td>
<td>1340</td>
<td>&lt; 3.3%</td>
<td>&lt; 4.4%</td>
</tr>
</tbody>
</table>

$^a$ *ROSAT* HRI

$^b$ *Chandra* LETGS

Note. — These are the pulsed fraction upper limits for RX J1856.5−3754 based on the Fourier searches discussed in §3.1. The highest normalized power found in each search is denoted by $P_{\text{max}}$ and the approximate number of independent trials (including $\dot{f}$ trials and gaps in the data) is given by $N_{\text{trials}}$ in units of $10^6$ trials.