

THE NEXT GEMINGA: SEARCH FOR RADIO AND X-RAY PULSATIONS FROM THE NEUTRON STAR IDENTIFIED WITH 3EG J1835+5918

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ABSTRACT

We report unsuccessful searches for pulsations from the neutron star RX J1836.2+5925, identified with the EGRET source 3EG J1835+5918. A 24 hr observation with the NRAO Green Bank Telescope at 820 MHz placed an upper limit on flux density of $17 \mu\text{Jy}$ for $P \gtrsim 10$ ms, and gradually increasing limits for $1 \lesssim P \lesssim 10$ ms. The equivalent luminosity is lower than that of any known pulsar, with the possible exception of the radio-quiet γ -ray pulsar Geminga. A set of observations with the *Chandra X-ray Observatory* HRC totaling 118 ks revealed no pulsar with $1 \text{ ms} \leq P \leq 10 \text{ s}$. The upper limit on its pulsed fraction is 35% assuming a sinusoidal pulse shape. The position of RX J1836.2+5925 in *Chandra* observations separated by 3 years is unchanged within errors, leading to an upper limit on its proper motion of $< 0.14'' \text{ yr}^{-1}$, or $v_t < 530 \text{ km s}^{-1}$ at $d = 800 \text{ pc}$, a maximum distance estimated from its thermal X-ray spectrum. With these null results, the properties of 3EG J1835+5918 and its X-ray counterpart RX J1836.2+5925 are consistent with a more distant or older version of Geminga, or perhaps a recycled pulsar. Having nearly exhausted the capabilities of current instrumentation at all wavelengths, it will likely fall to the *Gamma-ray Large Area Space Telescope* to discover pulsations from 3EG J1835+5918.

Subject headings: gamma rays: observations — stars: neutron — X-rays: individual (RX J1836.2+5925)

1. INTRODUCTION

The brightest of the “unidentified” high Galactic latitude EGRET sources (Hartman et al. 1999), 3EG J1835+5918 at $(\ell, b) = (89^\circ, +25^\circ)$, has long been associated with the X-ray-emitting neutron star RX J1836.2+5925, which remains its most plausible counterpart even though pulsations have not been detected at any wavelength. Unlike blazars, which are highly variable and have steeper γ -ray spectra, 3EG J1835+5918 shows no evidence for long-term variability, and its spectrum can be fitted by a relatively flat power law of photon index $\Gamma = 1.7$ from 70 MeV to 4 GeV, with a turn-down above 4 GeV (Reimer et al. 2001), similar to known γ -ray pulsars. RX J1836.2+5925 is the only optically undetected X-ray source in the γ -ray error box, all the others being classified as unlikely γ -ray emitters (Mirabal et al. 2000). The detection of RX J1836.2+5925 as a weak, ultrasoft source in the *ROSAT* All-Sky Survey (Mirabal & Halpern 2001) suggested that it is a thermally emitting neutron star that is either older or more distant than the γ -ray pulsar Geminga (Halpern & Ruderman 1993; Bignami & Caraveo 1996).

Observations using the *Chandra* Advanced CCD Imaging Camera (ACIS) and the *Hubble Space Telescope* (HST) further supported this interpretation (Halpern et al. 2002). Two components were required to fit the *Chandra* X-ray spectrum, a blackbody of $T \sim 3.5 \times 10^5 \text{ K}$ and a power law of photon index $\Gamma = 2.2 \pm 0.6$. The nonthermal X-ray component is important evidence of magnetospheric activity that is found in all γ -ray pulsars, but not in all cooling neutron stars. An optical upper limit of $V > 28.5$ from the *HST* verified the neutron star interpretation of RX J1836.2+5925 from its extreme X-ray-to-optical flux ratio, $f_X/f_V > 6000$. We also used the thermal X-ray spectrum and optical limit to bound the distance to RX J1836.2+5925 in the range $250 < d < 800 \text{ pc}$. The energetics of 3EG J1835+5918 are plausible for a pulsar at $d < 800 \text{ pc}$, since its γ -ray luminosity (assumed isotropic) is $3.8 \times 10^{34} (d/800 \text{ pc})^2 \text{ ergs s}^{-1}$, comparable to the spin-down power $\dot{E} = -I\Omega\dot{\Omega}$ of Geminga ($3.3 \times 10^{34} \text{ ergs s}^{-1}$). Efficiencies approaching 100% are achieved by those γ -ray pulsars having the smallest spin-down power.

Halpern et al. (2002) also searched for radio pulsations from RX J1836.2+5925 using the Jodrell Bank Lovell telescope at a frequency of 1.4 GHz, achieving an upper limit of $S_{1.4} < 0.1 \text{ mJy}$. Adopting an upper limit of $d < 800 \text{ pc}$, the pulsed pseudoluminosity limit of RX J1836.2+5925 is $L_{1.4} \equiv S_{1.4}d^2 < 0.064 \text{ mJy kpc}^2$. There are only four pulsars known with $L_{1.4} < 0.1 \text{ mJy kpc}^2$ (Camilo et al. 2002) in addition to Geminga (McLaughlin et al. 1999 and references therein).

In this paper, we report an even more sensitive search for radio pulsations from RX J1836.2+5925 using the NRAO Green Bank Telescope (GBT), as well as the first X-ray pulsation search with the *Chandra* High Resolution Camera (HRC-S). These investigations approach the sensitivity limits of existing instrumentation to search for the pulsar in 3EG J1835+5918.

2. GBT RADIO PULSAR SEARCH

RX J1836.2+5925 is circumpolar at the GBT, where on 2002 December 6 we observed it for 24 hr using the BCPM spectrometer (Backer et al. 1997). Due to the intermediate latitude of the target, with a relatively small predicted dispersion measure (DM) and low Galactic background temperature, we observed at a central frequency of 820 MHz, with a bandwidth of 48 MHz in each of two polarizations. The signals from corresponding polarization channels were summed in hardware, and the total-power samples from each of 96 frequency channels were sampled every $72 \mu\text{s}$ and recorded to disk for offline analysis.

We analyzed the data using standard pulsar search techniques, implemented in the PRESTO software package (Ransom et al. 2002). First we identified and excised radio-frequency interference. We then dedispersed the data in the DM range $0\text{--}110 \text{ cm}^{-3} \text{ pc}$, with resolution of $0.3 \text{ cm}^{-3} \text{ pc}$. This is twice the maximum Galactic DM predicted for this line of sight by the Cordes & Lazio (2002) electron density model; for the distance range of $250\text{--}800 \text{ pc}$, within which the neutron star likely lies (§ 1), the predicted DM range is $2\text{--}9 \text{ cm}^{-3} \text{ pc}$. Each time series contained 1.2 billion points, and would have been needlessly challenging to analyze. We therefore down-sampled the data to a resolution of 0.288 ms, resulting in

TABLE 1
Chandra HRC OBSERVATIONS OF RX J1836.2+5925

ObsID	Start Time (UT)	Live Time (s)	Counts
6182.....	2005 Feb 28 19:27	45,018	284
4606.....	2005 Mar 9 15:30	28,030	189
6183.....	2005 Mar 11 08:19	44,999	256
Total		118,047	729

much more reasonable time series of 300 million points. For a DM of $40 \text{ cm}^{-3} \text{ pc}$, the smearing caused by dispersion across one of the frequency channels is 0.3 ms, so that for smaller DMs the effective time resolution of the search was about 0.3 ms.

We performed the periodicity search using fast-Fourier techniques, and were sensitive to periods $P \gtrsim 1 \text{ ms}$. In order to improve sensitivity for a range of pulse duty cycles, we incoherently summed up to 16 harmonics of the data; for $P \gtrsim 10 \text{ ms}$, we maintained good sensitivity for duty cycles down to about $0.03P$. The sensitivity at long periods decreases gradually due to red noise, but this is not a significant concern for $P \lesssim 5 \text{ s}$. Unfortunately, we found no convincing pulsar candidates in this search.

Using the standard modification to the radiometer equation, assuming a pulse shape with 10% duty cycle, we were sensitive to pulsars with $P \gtrsim 10 \text{ ms}$ having a period-averaged flux density at 820 MHz of $\gtrsim 17 \mu\text{Jy}$, with gradually decreasing sensitivity for smaller periods. Converting this to the more usual 1.4 GHz pulsar search frequency with a typical spectral index of -1.6 (Lorimer et al. 1995) gives $S_{1.4} \lesssim 7 \mu\text{Jy}$. For a distance of 800 pc, this corresponds to $L_{1.4} \lesssim 5 \mu\text{Jy kpc}^2$. All known radio pulsars have a greater $L_{1.4}$ (Camilo et al. 2002).

Based on these results, it is therefore unlikely that RX J1836.2+5925 is a radio pulsar beaming toward the Earth. More likely, it is either beaming away, or is not an active radio pulsar at all.

3. CHANDRA HRC PULSAR SEARCH

Three observations of RX J1836.2+5925 totaling 118 ks of live time were performed between 2005 February 28 and 2005 March 11 using the *Chandra* HRC-S in timing mode, which has time resolution of $16 \mu\text{s}$, and provides absolute accuracy of $42 \mu\text{s}$, as determined from observations of the Crab pulsar.¹ Table 1 lists the basic parameters of the observations, including the number of photons extracted from a $1.2''$ radius aperture. The live time is 99.6% of the elapsed time, limited by event processing. The total number of photons detected from RX J1836.2+5925 is 729, of which 20 are estimated to be background (using nearby, source-free regions of the image). The count rates from the three observations are within 9% or less of the average count rate, 0.006 s^{-1} , consistent with no variation. The spatial distribution of photons is consistent with a point source. Originally conceived as a contiguous, 135 ks pointing, the observation could not be executed as planned because of new operational restrictions that came into effect. The resulting large gaps in time diminish the sensitivity to pulsations, because the increased number of independent frequencies and frequency derivatives that have to be searched yield more false candidates.

The total time span of the observations from beginning to end is $T = 9.6 \times 10^5 \text{ s}$, which determines the independent intervals for frequency and frequency derivative, $\Delta f = 1/2T$ and $\Delta \dot{f} = 1/T^2$, respectively. We chose a frequency step size $\delta f = 2 \times$

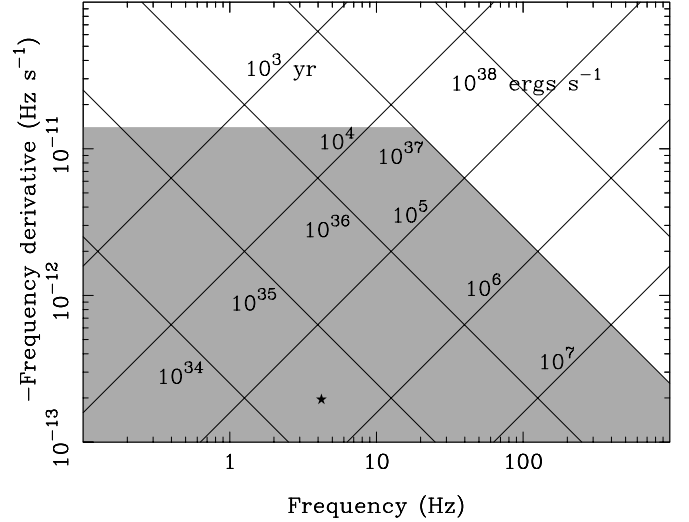


FIG. 1.—Parameter space (f, \dot{f}) searched for X-ray pulsations from RX J1836.2+5925, shown shaded. The step size $\delta f = 4 \times 10^{-13} \text{ Hz s}^{-1}$, and the search includes $\dot{f} = 0$. Lines of constant \dot{E} and τ_c are shown. The star indicates the parameters of Geminga.

10^{-7} Hz to oversample the independent frequency interval by a factor of ≈ 2.5 , and $\delta \dot{f} = 4 \times 10^{-13} \text{ Hz s}^{-1}$ to achieve a similar oversampling factor for frequency derivative.

We transformed the photon arrival times to Barycentric Dynamical Time, and did coherent searches of the full data set using the discrete Fourier transform technique, also known as the Rayleigh or Z_1^2 test (Buccheri et al. 1983). We searched the entire range of (f, \dot{f}) parameter space for a pulsar that has $0.1 \leq f \leq 1000 \text{ Hz}$, characteristic age $\tau_c \equiv -f/2\dot{f} > 20 \text{ kyr}$, as well as $\dot{E} = -4\pi^2 I f \dot{f} \leq 10^{37} \text{ ergs s}^{-1}$. In practice, we found it simplest to confine the search to the region shaded in Figure 1, bounded by $\dot{f} \leq 1.4 \times 10^{-11} \text{ Hz s}^{-1}$ for $f < 17.9 \text{ Hz}$, and $\dot{f} \leq 2.5 \times 10^{-10} f^{-1} \text{ Hz s}^{-1}$ for $f \geq 17.9 \text{ Hz}$. The total number of trials thus defined is $\approx 1.6 \times 10^{10}$, an oversampling of the independent trials by a factor of ≈ 7 .

This is a liberal search range, which is justified as follows. RX J1836.2+5925 would have a blackbody temperature greater than its observed $\sim 3.5 \times 10^5 \text{ K}$ if it were younger than 20 kyr; an independent argument for an older age is given in § 4. It would have a wind nebula or stronger nonthermal X-ray component if $\dot{E} > 10^{37} \text{ ergs s}^{-1}$. In view of the distance limit $d < 800 \text{ pc}$, the ratio $L_X/\dot{E} \leq 10^{-6}$ if $\dot{E} = 10^{37} \text{ ergs s}^{-1}$, a smaller ratio than all other pulsars, which typically have $10^{-4} < L_X/\dot{E} < 10^{-2}$. Thus, it is unlikely that \dot{E} is as large as $10^{37} \text{ ergs s}^{-1}$.

The range of parameters searched also includes all of the known millisecond (recycled) pulsars, and is effective as long as the pulsar does not have a neutron star binary companion. The deep *HST* limit, corresponding to absolute magnitude $M_V > 19$ at $d = 800 \text{ pc}$, rules out the more common white dwarf companions.

No significant pulsed signal was detected. The largest values of Z_1^2 found were ≈ 44 . The theoretical distribution of Z_n^2 follows that of χ^2 with $2n$ degrees of freedom. For $n = 1$, the distribution is an exponential with a mean of 2, so the single-trial probability that $Z_1^2 \geq 44$ by chance is 2.8×10^{-10} . This is expected to arise randomly in $\approx 10^{10}$ independent trials. Leahy et al. (1983) showed that to detect sinusoidal pulsation with amplitude (pulsed fraction) f_p at a power level $S = Z_1^2$ with 50% probability, the number of photons needed is $N = 2S/f_p^2$. In our case, $N = 729$ (709 corrected for background), so we find $f_p \leq 0.35$, corresponding to $Z_1^2 \leq 44$. We verified this analytic expression by examining folded

¹ See <http://cxc.harvard.edu/cal/>.

light curves at the periods associated with the maximum values of Z_1^2 .

It is not surprising that the pulsed fraction of a γ -ray pulsar in X-rays should be less than 35%. This is not a very sensitive limit considering that other γ -ray pulsars whose soft X-rays are predominantly thermal (Geminga, PSR B1055–52, possibly PSR B0656+14) have even smaller pulsed fractions (30%, 21%, and 12%, respectively; De Luca et al. 2005). In these cases, the pulse profiles are quasi-sinusoidal. The Z_1^2 test is therefore a good one for RX J1836.2+5925, whose X-rays are also dominated by a soft thermal source within the response of the *Chandra* HRC, although the result is not very restrictive in this case. We also note that the Vela pulsar has a more complicated pulse shape, while its pulsed fraction is only 9% (Manzali et al. 2007).

4. CHANDRA ASTROMETRY

In order to test for proper motion of the neutron star, we compared the position of RX J1836.2+5925 on the HRC with the ACIS position obtained 3 years earlier (Halpern et al. 2002). First, we updated the ACIS position to the USNO-B1.0 system using optically identified sources in the ACIS image. The result is R.A. = $18^{\text{h}}36^{\text{m}}13.685^{\text{s}}$, decl. = $+59^{\circ}25'29.95''$ (J2000.0), and differs from the previously used USNO-A2.0 system by $0.3''$. Then we registered the HRC image to the ACIS image using seven X-ray sources in the vicinity of RX J1836.2+5925, which required a zero-point shift of the HRC image of $+0.052^{\text{s}}$ in R.A. and $+0.89''$ in decl. The resulting HRC position of RX J1836.2+5925 is R.A. = $18^{\text{h}}36^{\text{m}}13.674^{\text{s}}$, decl. = $+59^{\circ}25'30.15''$ (J2000.0).

The difference between the positions of RX J1836.2+5925 in 2002 and 2005 is therefore only $0.21''$, which is comparable to their combined statistical errors. In order to bound the possible proper motion, we adopt an upper limit that is twice this difference, or $0.42''$, corresponding to $\mu < 0.14'' \text{ yr}^{-1}$. This allows the neutron star to have traveled from a birth in the Galactic plane to its present position in $6.4 \times 10^5 \text{ yr}$ or longer, which is not an unreasonable age for its X-ray temperature. At the maximum distance of 800 pc, the limit on μ corresponds to a tangential velocity limit $v_t < 530 \text{ km s}^{-1}$, which is typical for radio pulsars.

5. DISCUSSION AND CONCLUSIONS

Even in the absence of detectable pulsations, RX J1836.2+5925 remains the leading (and only) candidate for identification with 3EG J1835+5918. Its soft X-ray spectrum, and absence of optical and radio emission, support the hypothesis that it is an older and possibly more distant cousin of the Geminga pulsar. The upper limit on proper motion that we derived is a significant new observational constraint, allowing an age of at least $6.4 \times 10^5 \text{ yr}$ for RX J1836.2+5925 if it was born in the Galactic plane. This compares favorably with the characteristic age $\tau_c = 3.4 \times 10^5 \text{ yr}$ of Geminga, and is consistent with a surface temperature of only $\sim 3.5 \times 10^5 \text{ K}$, compared with $4.8 \times 10^5 \text{ K}$ for Geminga (Caraveo et al. 2004; Jackson & Halpern 2005; Kargaltsev et al. 2005).

Assuming that the age and distance of RX J1836.2+5925 are both larger than those of Geminga, it is likely that 3EG J1835+5918 is a maximally efficient γ -ray pulsar close to its death line (Chen & Ruderman 1993), following the trend of γ -ray efficiency increasing with decreasing spin-down power (Thompson et al.

1997, 1999). Alternatively, we cannot rule out the possibility that RX J1836.2+5925 is a millisecond pulsar with similar spin-down power and magnetospheric gap voltage as Geminga. If so, its thermal X-ray emission may be due to surface reheating by a magnetospheric accelerator.

6. PROSPECTS FOR GLAST

It is not now possible to make a significantly more sensitive search for X-ray pulsations from RX J1836.2+5925, as the operational limitations of *Chandra* no longer allow long, contiguous pointings. While *XMM-Newton* is in principle more sensitive, it has not been used to observe RX J1836.2+5925, which lies near the Earth-avoidance zone of the satellite orbit, with maximum allowed pointing durations of $\approx 20 \text{ ks}$.

Finally, the upcoming *Gamma-ray Large Area Space Telescope* (*GLAST*) may be the best hope of detecting pulsations from 3EG J1835+5918. *GLAST* will certainly reduce the positional uncertainty of 3EG J1835+5918, which will be an independent test of association with RX J1836.2+5925, and additional motivation for a dedicated pulsar search. For this, a sufficiently long, pointed observation is best, as argued by Ransom (2007).

We estimate the expected *GLAST* count rate from 3EG J1835+5918 using its photon flux of $5.9 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ between 100 MeV and 4 GeV (Reimer et al. 2001). Assuming an average on-axis effective area of 5000 cm^2 for the *GLAST* Large Area Telescope (LAT) in this energy range, the predicted count rate is 0.003 s^{-1} . A more detailed calculation, convolving the spectrum of 3EG J1835+5918 from Figure 3 of Reimer et al. (2001) with the LAT on-axis effective area curve,² predicts a similar rate of 0.0028 s^{-1} in the 50–4000 MeV range. This is almost half the count rate from the *Chandra* HRC, and holds great promise for a pulsar discovery.

It is likely that *GLAST* will succeed where *Chandra* failed because, unlike thermal X-rays, γ -rays have sharp peaks with pulsed amplitude approaching 100%. In 1 week of elapsed time, including Earth blockage, *GLAST* can collect as many photons from 3EG J1835+5918 as we have obtained using *Chandra*. On-source time in a pointed observation of 3EG J1835+5918 can be higher than average because the source is close to the ecliptic pole. Also, Galactic background is negligible at these coordinates, $(\ell, b) = (89^{\circ}, +25^{\circ})$. If *GLAST* is successful, the *Chandra* photons analyzed here may yet be used to find a coincident period and period derivative with confidence, thus establishing the identity of 3EG J1835+5918 with RX J1836.2+5925, and determining its physical parameters.

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² See http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.

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