IS CALVERA A GAMMA-RAY PULSAR?

J. P. HALPERN

Astronomy Department, Columbia University, 550 West 120th Street, New York, NY 10027-6601, USA; jules@astro.columbia.edu

Received 2011 March 16; accepted 2011 June 10; published 2011 June 23

ABSTRACT

Originally selected as a neutron star (NS) candidate in the ROSAT All-Sky Survey, 1RXS J141256.0+792204 (“Calvera”) was discovered to be a 59 ms X-ray pulsar in a pair of XMM-Newton observations by Zane et al. Surprisingly, their claimed detection of this pulsar in Fermi γ-ray data requires no period derivative, severely restricting its dipole magnetic field strength, spin-down luminosity, and distance to small values. This implies that the cooling age of Calvera is much younger than its characteristic spin-down age. If so, it could be a mildly recycled pulsar, or the first “orphaned” central compact object (CCO). Here we show that the published Fermi ephemeris fails to align the pulse phases of the two X-ray observations with each other, which indicates that the Fermi detection is almost certainly spurious. Analysis of additional Fermi data also does not confirm the γ-ray detection. This leaves the spin-down rate of Calvera less constrained, and its place among the families of NSs uncertain. It could still be either an ordinary pulsar, a mildly recycled pulsar, or an orphaned CCO. 

Key words: pulsars: individual (1RXS J141256.0+792204, PSR J1412+7922, Calvera) – stars: neutron

1. INTRODUCTION

The neutron star (NS) candidate 1RXS J141256.0+792204, dubbed “Calvera” (Rutledge et al. 2008), was selected from the ROSAT All-Sky Survey, and observed by Chandra (Rutledge et al. 2008; Shevchuk et al. 2009). A deep radio pulsar search showed that it is radio quiet (Hessels et al. 2007). It was not until a pair of XMM-Newton observations was obtained with high time resolution that Zane et al. (2011) discovered 59 ms pulsations from Calvera. The classification of Calvera among the families of NSs is not yet understood. Its X-ray spectrum is characterized as a blackbody of temperature ≈0.2 keV, or a hydrogen atmosphere of T ∼ 0.1 keV (Shevchuk et al. 2009; Zane et al. 2011). Two-temperature models provide a better fit, and the surface temperature must be nonuniform because pulsations are seen. Calvera’s properties distinguish it from seven isolated NSs (INSs; Haberl 2007), also discovered by ROSAT, which are slowly rotating (P ∼ 3–11 s), cooler NSs in the solar neighborhood. X-ray timing and spectroscopy and kinematic studies of the INSs indicate that they have strong magnetic fields, Bs ≈ 2 × 1013 G, and are ≈106 years old (Kaplan & van Kerkwijk 2009). Calvera is at least twice as hot as the INSs, indicating an age ≤105 yr according to minimal NS cooling curves (Page et al. 2004, 2009). Even though it is at high Galactic latitude (ℓ, b) = (118°, +37°), if Calvera is a passively cooling NS it must be close to its birthplace in the disk, implying a maximum distance of a few hundred parsecs. Depending on the X-ray spectral model fitted, the column density is consistent with a range of values that does not further constrain the distance. Based on the spectral fits of Zane et al. (2011), the bolometric flux is uncertain by about a factor of two, and the luminosity is LX ≈ 1.7 × 1034 d2,300 erg s−1, where d,300 is the distance in units of 300 pc. Calvera remains radio quiet even after a deeper search for radio pulsations at 59 ms (Zane et al. 2011).

Analyzing data from the Fermi Large Area Telescope (LAT), Zane et al. (2011) claimed that 59 ms pulsations are detected from 1RXS J141256.0+792204 at > 100 MeV. Apart from the marginal significance of the detection, this result is surprising because their ephemeris requires no frequency derivative over the 21 month time span analyzed. Their effective 2σ upper limit is |f| < 2.6 × 10−16 Hz s−1, implying spin-down power $E = −4π^2 I f^2 < 1.7 × 10^{32}$ erg s−1, characteristic age $τ_c ≡ −f/2f' > 1.0 × 10^9$ yr, and magnetic field strength $B_s > 3.2 × 10^{19} \sqrt{-ff''} < 7.4 × 10^9$ G. Here we assume a moment of inertia I = 1055 g cm2, Bs is the equatorial surface dipole field, and frequency f = 16.89 Hz. (We are unable to account for their quoted upper limit $B_s < 5 × 10^{10}$ G, which would allow $f > −1.2 × 10^{−14}$ Hz s−1.)

These timing parameters imply that 1RXS J141256.0+792204 is not just a passively cooling NS but is converting a large fraction of its meager spin-down power into γ-rays. The quoted pulsed γ-ray luminosity is $L_{γ} ≈ 1.5 × 10^{32} d_{,300}^2$ erg s−1 assuming isotropic emission. All other γ-ray pulsars have $E > 2 × 10^{33}$ erg s−1 (Abdo et al. 2010a); Calvera would be the least energetic γ-ray pulsar by an order of magnitude. In this Letter, we show that the Fermi detection of Calvera is almost certainly false. We then discuss the implications for the nature of Calvera.

2. XMM-NEWTON TIMING OF THE PULSATIONS FROM 1RXS J141256.0+792204

We reduced the now archival EPIC pn CCD data from the two XMM-Newton observations of Calvera listed in Table 1. These were taken in small window mode with 5.7 ms time resolution, and were separated by 40 days. The data were processed with SAS version xmmmsas_20090112_1802-8.0.0. We extracted photons in the 0.15–2 keV band from a 20′′ radius aperture around the source. Background was taken from an adjacent region on the CCD. We applied the conversion to Barycentric Dynamical Time using the precise Chandra position of the source from Shevchuk et al. (2009), R.A. = 14°12′55″58′′, decl. = +79°22′03″7′′ (2000.0). The 0′6 position uncertainty is a negligible source of error on the absolute timing. Table 1 lists the peak frequencies of the two XMM-Newton observations derived from a Z21 power spectrum (Rayleigh test; Strutt 1880; Buccheri et al. 1983). We folded each light curve at the peak period. The pulse profiles are shown in Figure 1, where we have aligned them arbitrarily in phase. The two profiles have a consistent, quasi-sinusoidal or triangular shape, and a pulsed fraction of
aligned arbitrarily in phase. Background has been subtracted and the counts are the observations. The 2 difference of the frequencies by the time interval between frequency derivative by propagating the errors and dividing the data in Table 1, we calculate an upper limit on the frequency measurements is insufficient to join these widely spaced counterpart.

Figure 1. Two XMM-Newton pulse profiles of 1RXS J141256.0+792204 in the 0.15–2 keV band, each folded on its peak frequency from Table 1, and aligned arbitrarily in phase. Background has been subtracted and the counts are normalized to 1. Two cycles are plotted.

≈18%. The precise agreement between the frequencies at the 10^{-7} fractional level argues against any orbital motion (but see below), which is supported by the absence of an optical counterpart.

As noted by Zane et al. (2011), the precision of the two frequency measurements is insufficient to join these widely spaced observations coherently and obtain more precise timing parameters. Since the measured frequencies agree within their errors, we can only derive an upper limit on the spin-down rate. Using the data in Table 1, we calculate an upper limit on the frequency derivative by propagating the errors and dividing the difference of the frequencies by the time interval between the observations. The 2σ upper limit is |\dot{f}| < 2.0 \times 10^{-12} \text{Hz s}^{-1}. The corresponding 2σ limits on the spin-down properties are \dot{E} < 1.3 \times 10^{36} \text{erg s}^{-1}, \tau_\gamma > 1.3 \times 10^5 \text{yr}, and B_0 < 6.5 \times 10^{11} \text{G}. These are the limits that we will conclude are the best currently available. They are consistent with the Zane et al. (2011) results of the same analysis.

Using Fermi LAT data, Zane et al. (2011) claimed to detect γ-ray pulsations from 1RXS J141256.0+792204 by searching coherently a 21 month span from 2008 August to 2010 April using the Z^2 test. Although no imaging detection of a source at this position was reported, searching both \dot{f} and f around the X-ray measured values, they found a peak power Z^2 = 26.2 with the following ephemeris: epoch t_0 = 55094 MJD, f = 16.892401975(2) Hz, \phi = -1.2(7) \times 10^{-16} \text{Hz s}^{-1}. Since this ephemeris spans the dates of the XMM-Newton observations in 2009 August and October, it can be used fold the X-ray photons, and the pulse profiles so derived should align in phase. Zane et al. (2011) did not perform this test. The result is shown in Figure 2. The test fails because the light curves folded according to the trial ephemeris are out of phase by 0.35 cycles (21 ms). As we discuss below, this is much larger than the maximum ~3 ms uncertainty due to the 5.7 ms CCD frame time. Therefore, we conclude that the ephemeris represents a noise peak in the power spectrum of (probably) background photons, not a true detection of pulsations.

This test does not involve the phasing of the γ-ray pulse with respect to the X-ray pulse, nor is it sensitive to uncertainties on the Fermi ephemeris parameters. This is because the coherent ephemeris is a phase ephemeris. It specifies the phase of the γ-ray pulse with respect to the X-ray pulse, nor is it sensitive to uncertainties on the Fermi ephemeris parameters. This is because the coherent ephemeris is a phase ephemeris. It specifies the phase of the γ-ray pulse with respect to the X-ray pulse, nor is it sensitive to uncertainties on the Fermi ephemeris parameters.

Table 1

| ObsID       | Date (UT)     | Date (MJD)     | Span (s) | Exp. (s) | Frequency (Hz)^a | Z^2    |
|-------------|---------------|----------------|----------|----------|------------------|--------|
| 0601180101  | 2009 Aug 31   | 55,074.30      | 19,911   | 13,941   | 16.8924052(25)   | 141.1  |
| 0601180201  | 2009 Oct 10   | 55,114.18      | 27,816   | 19,477   | 16.8924041(15)   | 201.9  |

Note. ^a 1σ error in parenthesis.

Figure 2. Same data as in Figure 1, now folded on the supposed Fermi ephemeris (Zane et al. 2011) that spans these epochs (see the text). The bin size of the 10 bin light curve is 5.9 ms, comparable to the CCD frame time of 5.7 ms. Evidently the ephemeris does not phase-align the X-ray pulse profiles.

\[\dot{f} \approx f - \frac{1}{2} f t (t - t_0)\]

where the 007 cycles and "Fermi Ephemeris" are contained well within that span. The quoted Fermi uncertainties, \sigma_f(f) = 2 \times 10^{-9} \text{Hz} and \sigma_f(f) = 7 \times 10^{-17} \text{Hz s}^{-1}, can contribute only tiny drifts in relative phase, \Delta \phi = \sigma_f(f) T_X = 0.007 cycles and \Delta \phi = 0.5 \sigma_f(f) T_X = 0.0004 cycles, respectively, over the T_X = 40 day interval between the X-ray observations. Even these are upper limits, as the errors are covariant.

Our analysis does depend on the stability of EPIC pn timing in small window mode. Considerable effort has gone into calibrating the relative and absolute timing of this particular mode and maintaining the accuracy of the photon time assignments in the processing chain. The absolute accuracy of the XMM-Newton clock is better than 0.6 ms (Kirsch et al. 2004). We have carried out extensive investigations of pulsars using the pn small window mode, and empirical checks for consistency show that the absolute times are at least as accurate as the ~3 ms uncertainty due to the 5.7 ms CCD frame time. We summarize two of these studies here: a coherent ephemeris for the 237 ms pulsar Geminga with AGILE (Pellizzoni et al. 2009) and Fermi (Abdo et al. 2010b) to < 1 ms. These agree with earlier results comparing EGRET and ASCA (Jackson & Halpern 2005). In an extensive campaign on the 105 ms pulsar PSR J1852+0040 (Halpern & Gotthelf 2010), 16 XMM-Newton observations and seven Chandra observations (with time resolution 3 ms) spanning 4.8 years are fitted by a quadratic phase ephemeris with rms...
phase residuals of 3.4 ms. This demonstrates that XMM-Newton and Chandra agree in absolute time to better than 3 ms.

Our analysis does not make use of the EPIC MOS detector timing data that were obtained simultaneously with the pn. Zane et al. (2011) noted that the MOS detector’s timing mode is not well calibrated, and they did not use it for timing analysis.

3. DISCUSSION OF PREVIOUS FERMI ANALYSIS

We address here reasons why one might consider the Fermi detection of Calvera to be real despite our negative evidence. First, Zane et al. (2011) suggest that actually a more conservative upper limit on the frequency derivative from Fermi should be allowed, $|\dot{f}| < 10^{-15} \text{ Hz s}^{-1}$. Still, its effect over the 40 day interval between X-ray observations would be negligible, and it would not change the outcome of our X-ray phase comparison. It is not clear why they entertain this possibility, since such a value would contribute 1.5 extra cycles of rotation over the 21 month span of their ephemeris. If $\dot{f}$ actually turns out to be $-1 \times 10^{-15} \text{ Hz s}^{-1}$, it would be a different ephemeris from the published one, and the originally published detection would be spurious. For that matter, the frequency of the pulsar could also turn out to differ by more than one Fourier bin (1/T$_{\gamma}$, where T$_{\gamma}$ is the 21 month span of the Fermi data) from the published Fermi ephemeris, and still be consistent with the X-ray measured value. In this case as well, the originally claimed γ-ray detection is just noise.

Second, it may be argued that, while the fitted ephemeris corresponds to the average values of $f$ and $\dot{f}$ over the time span, there could be timing noise that smears the pulse, while the signal is not strong enough to fit such trends with higher order terms. Under this hypothesis, the phase drift between the two X-ray observations is a manifestation of timing noise. We consider this unlikely because the fitted $f$ is already consistent with zero. Any detectable timing noise would vary the sign of $\dot{f}$, which has not been seen in any isolated pulsar apart from glitch discontinuities. A phase drift of 0.35 cycles over 40 days would require an effective $\dot{f} = -5.9 \times 10^{-14} \text{ Hz s}^{-1}$ over this time, almost 500 times the mean value of $-1.2 \times 10^{-16} \text{ Hz s}^{-1}$. This seems unlikely, as does a glitch that is not also detected in the X-ray measured value. No pulsar with $T > 20$ Myr has been observed to glitch (Espinoza et al. 2011).

As an alternative to timing noise, it may be hypothesized that the X-ray phase shift over 40 days is evidence of binary motion, i.e., a planetary companion. Such an explanation would require the orbital period to be much less than the 21 month span of the Fermi ephemeris, but longer than the durations of the individual XMM-Newton pointings, which are 5.5 hr and 7.7 hr, respectively. We consider that 1 day $< P_{\text{orb}} < 100$ days covers the applicable range. Under the binary hypothesis, the projected radius $a_{\text{rs}} \sin i$ of the NS orbit falls in a narrow range. The Roemer delay $2 a_{\text{rs}} \sin i / c$ must be $\geq 21$ ms to produce the phase shift, but $\leq 59$ ms so as not to smear out the supposed γ-ray pulsations. Combining these requirements, for $m_{\text{ns}} = 1.4 M_{\odot}$ we find that

$$20 M_{\oplus} \leq \left( \frac{P_{\text{orb}}}{100 \text{ days}} \right)^{2/3} m_p \sin i \leq 60 M_{\oplus}. $$

This corresponds to a minimum planet mass of $m_p = 20/\sin i$ Earth masses, and a maximum of $4/\sin i$ Jupiter masses, the latter for $P_{\text{orb}} = 1$ day. More likely the γ-ray ephemeris is spurious, and the 0.35 cycle phase shift is a random number, not evidence of a planet.

Other aspects of the Zane et al. (2011) analysis are unusual. By their own description, the γ-ray signal is marginal, with $Z_1^2 = 26.2$, and its significance depends on the number of independent trials in the search. The trials can be assessed using the X-ray uncertainties on the timing parameters in Section 2, $\sigma_x(f) = 1.5 \times 10^{-6}$ Hz and $\sigma_x(\dot{f}) = 1 \times 10^{-12} \text{ Hz s}^{-1}$, and the $T_y = 21$ month span of the Fermi data. The number of independent trials in the two-dimensional Fermi search should be at least $4 \sigma_x(f) T_y \approx 330$ for frequency, and $\sigma_x(\dot{f}) T_y^2 \approx 3000$ for frequency derivative. These represent a search of independent frequencies in the ±2σ interval around the XMM-Newton measured $f$ and independent frequency derivatives ranging from zero to the $\sim 2\sigma$ limit, i.e., only negative $\dot{f}$. If so, the expected number of noise peaks of power $Z_1^2 \geq 26.2$, obtained by multiplying the $1 \times 10^6$ trials by the single-trial probability, $e^{-26.2/2} = 2 \times 10^{-6}$, is of order unity. The oversampling by a factor of 10 that was performed further reduces the statistical significance. The crux of their argument must be that, since the value of $f$ in the discovered signal is consistent with zero, almost no trials in $\dot{f}$ were needed to find it. Only this would allow that the chance probability of the result is $\sim 7 \times 10^{-4}$. But they do not display the power spectrum for the complete search. Instead, they say that they did not find false detections over a range of parameters much wider than the X-ray uncertainties. It is not stated what they consider a false detection, and we are not shown the values of the highest peaks in the extended search. Therefore, we don’t know what to make of this argument. Finally, the absence of the γ-ray source in a spatial image is also worrisome, especially since the position is at high Galactic latitude with minimal confusing diffuse background. So there is no supporting evidence of a source at this position.

4. ANALYSIS OF NEW FERMI DATA

For completeness, we extracted and reduced Fermi data using the same event filtering and methods described by Zane et al. (2011). We first extracted the identical 631 day time span, 2008 August 4–2010 April 27, recovering 2750 photons, similar to their 2518 photons. A $Z_1^2$ search covering the ±3σ uncertainty on their Fermi frequency derivative recovers the candidate peak at $f = 16.892401976$, as shown in Figure 3. The peak power, $Z_1^2 = 24.4$, is consistent with their value of 26.2.
We then applied the same method to the full data set now available, comprising 4764 photons collected up to 2011 May 19 (33 months). This increases the number of photons by 73%. A search of the same ephemeris parameters does not yield increased power at the claimed frequency. Rather, the peak previously seen is reduced to $Z_f^2 = 16.0$ (Figure 4), indicating that it was just noise. We regard this result as direct support of our inference that the supposed Fermi detection was not real. A wider search of thousands of trials in $f$ is not meaningful, for the reasons discussed above.

5. CONCLUSIONS

In summary, the incorrect phasing of the X-ray observations of Calvera using the claimed Fermi ephemeris led us to conclude that the $\gamma$-ray detection is probably spurious. Then, extending the Fermi analysis from 21 to 33 months rendered the candidate signal insignificant. Here we comment on the implications for the nature of Calvera using the claimed Fermi ephemeris. The region of $(P, \dot{P})$ space where they were born, which is also where the supposed mildly recycled pulsars are found (Belczynski et al. 2010). An orphaned CCO would be distinguished from a single, recycled pulsar by its residual thermal X-ray luminosity. An orphaned CCO could be recognized as a thermal X-ray source, depending on its distance, while it is up to $10^{10}$--$10^{16}$ yr old (not the characteristic age, which is orders of magnitude larger than the real age of a CCO). The known CCOs have X-ray temperatures in the range $0.2$--$0.4$ keV. Calvera, being cooler than this and less luminous than a young CCO by an order of magnitude or more, could be an evolved stage of a passively cooling CCO. It is possible, therefore, that 1RXS J141256.0+792204 is the first orphaned CCO to be recognized.

These scenarios can be distinguished by the spin-down rate of the pulsar. If $B_r = 6 \times 10^{11}$ G and $\tau_c > 1.5 \times 10^5$ yr, Calvera is probably an ordinary pulsar. If $B_r = 1 \times 10^{11}$ G and $\tau_c = 4 \times 10^6$ yr, it could be an orphaned CCO younger than $\tau_c$, or a spin-powered, mildly recycled pulsar. If $B_r = 1 \times 10^{10}$ G and $\dot{E} = 3 \times 10^{33}$ erg s$^{-1}$, its spin-down power is probably insufficient to heat its surface, and an orphaned CCO would be required instead of a mildly recycled pulsar to explain its X-ray luminosity and temperature. Even though Calvera is not (yet) detected in $\gamma$-rays, an X-ray timing study is straightforward, and should detect its spin-down in $\approx 1$ yr even if its magnetic field strength is only $\approx 10^{10}$ G.

We thank Eric Gotthelf for discussions and assistance with the data. This investigation is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

REFERENCES

Abdo, A. A., et al. 2010a, ApJS, 187, 460
Abdo, A. A., et al. 2010b, ApJ, 720, 272
Belczynski, K., Lorimer, D. R., Ridley, J. P., & Curran, S. J. 2010, MNRAS, 407, 1245
Buccheri, R., et al. 1983, A&A, 128, 245
Espinoza, C. M., Lyne, A. G., Stappers, B. W., & Kramer, M. 2011, MNRAS, 414, 1679
Faucher-Giguère, C.-A., & Kaspi, V. M. 2006, ApJ, 643, 332
Gotthelf, E. V., Forna, R., & Halpern, J. P. 2010, ApJ, 724, 1316
Haberl, F. 2007, Ap&SS, 308, 181
Halpern, J. P., & Gotthelf, E. V. 2010, ApJ, 709, 436
Halpern, J. P., & Gotthelf, E. V. 2011, ApJ, 733, L28
Hessels, J. W. T., Stappers, B. W., Rutledge, R. E., Fox, D. B., & Shevchuk, A. H. 2007, A&A, 476, 331
Jackson, M. S., & Halpern, J. P. 2005, ApJ, 633, 1114
Kaplan, D. L., & van Kerkwijk, M. H. 2009, ApJ, 705, 798
Kirsch, M. G. F., et al. 2004, Proc. SPIE, 5165, 85
Page, D., Lattimer, J. M., Prakash, M., & Steiner, A. W. 2009, ApJ, 691, 1633
Pelizzoni, A., et al. 2009, ApJ, 691, 1633
Rutledge, R. E., Fox, D. B., & Shevchuk, A. H. 2008, ApJ, 672, 1137
Shevchuk, A. H., Fox, D. B., & Rutledge, R. E. 2009, ApJ, 705, 391
Strutt, J. W. 1880, Phil. Mag., 10, 73
Zane, S., et al. 2011, MNRAS, 410, 2428