X-RAY MEASUREMENT OF THE SPIN-DOWN OF CALVERA: A RADIO- AND GAMMA-RAY-QUIET PULSAR

J. P. HALPERN, S. BOGDANOV, AND E. V. GOTTHELF

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

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1. INTRODUCTION

The neutron star (NS) candidate 1RXS J141256.0+792204, dubbed “Calvera” by Rutledge et al. (2008), was selected from the ROSAT All-Sky Survey and observed by Chandra (Rutledge et al. 2008; Shevchuk et al. 2009). It was not until a pair of XMM-Newton observations was obtained with high time resolution that Zane et al. (2011) discovered the 59 ms pulsations from Calvera. The X-ray emission from Calvera is best described by a two-temperature (blackbody or hydrogen atmosphere) spectrum, with $kT$ in the range 0.1–0.25 keV (Shevchuk et al. 2009; Zane et al. 2011). The fitted column density in these models is equal to or greater than the Galactic value of $N_H = 2.7 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005), which, at its high Galactic latitude of $+37^\circ$, leaves Calvera’s distance highly uncertain. Its bolometric luminosity is $L_X \approx 1.2 \times 10^{35}$ erg s$^{-1}$, where $d_{500}$ is distance in units of 300 pc.

Calvera remains radio quiet even after deep searches for radio pulsations at the known period (Hessels et al. 2007; Zane et al. 2011). Analyzing data from the Fermi Large Area Telescope (LAT), Zane et al. (2011) concluded that γ-ray pulsations are detected from Calvera at $>100$ MeV. Halpern (2011) reanalyzed the XMM-Newton timing data in detail together with additional Fermi data, showing that the claimed Fermi detection was not real.

Calvera is of interest largely because its classification among the families of NSs is unclear, and it may occupy a unique role. Its properties distinguish it from the seven other isolated NSs (INSs; Haberl 2007) that were discovered by ROSAT, which are slowly rotating ($P = 3$–$11$ s), cooler NSs in the solar neighborhood (Figure 1). X-ray timing and spectroscopy and kinematic studies of the INSs indicate that they have strong magnetic fields, $B_s \approx 2 \times 10^{13}$ G, and are $\approx 10^6$ yr old (Kaplan & van Kerkwijk 2009). Calvera has at least twice the temperature of the INSs, but its age and magnetic field strength were undetermined until now. These unknowns allowed Zane et al. (2011) and Halpern (2011) to hypothesize that Calvera is either a mildly recycled pulsar (as defined by Belczynski et al. 2010) or the first candidate for the elusive descendants of the central compact objects (CCOs) in supernova remnants, thermally emitting NSs that have weak dipole fields in the range $(0.3$–$1) \times 10^{13}$ G (Gotthelf et al. 2013). However, if $B > 10^{11}$ G, it could just be an ordinary rotation-powered pulsar. In this paper, we report the detection of Calvera’s spin-down, which reveals its characteristic age, spin-down power, and dipole magnetic field strength. We also derive a new, interesting upper limit on its γ-ray luminosity.

2. X-RAY OBSERVATIONS

A new observation of Calvera was obtained using the Chandra Advanced Camera for Imaging and Spectroscopy (ACIS; Garmire et al. 2003) operated in continuous-clocking (CC) mode to provide a time resolution of 2.85 ms. To achieve fast timing in CC mode, one spatial dimension of the CCD image (the row number) is lost. ACIS has 0.5 pixels, comparable to the on-axis point-spread function. The target was placed on the back-illuminated ACIS-S3 CCD. Due to scheduling restrictions, the observation was split into two parts separated by 5 days in 2013 February, as listed in Table 1. All data reduction and analysis were performed with the Chandra Interactive Analysis of Observation software (CIAO; Fruscione et al. 2006) version 4.5, using the calibration database (CALDB) version 4.1.3. We extracted photons from five columns around the pulsar position and transformed their arrival times to the solar system barycenter in barycentric dynamical time (TDB) using the

Online-only material: color figures


**Table 1**

| Mission       | Instr/Mode | ObsID   | Date (UT) | Date (MJD) | Exp. (s) | Photons \(a\) | Frequency \(b\) (Hz) | \(Z_1^2\) |
|---------------|------------|---------|-----------|------------|----------|-----------------|----------------------|----------|
| XMM-Newton    | EPIC-pn/| 0601180101 | 2009 Aug 31 | 55,074.30  | 13,941   | 7703            | 16.8924052(25)       | 141.1    |
|               | SW        |         |           |            |          |                 |                      |          |
| XMM-Newton    | EPIC-pn/| 0601180201 | 2009 Oct 10 | 55,114.18  | 19,477   | 10,515          | 16.8924041(15)       | 201.9    |
|               | SW        |         |           |            |          |                 |                      |          |
| Chandra       | ACIS-S3/CC| 13788   | 2013 Feb 12 | 56,335.81  | 19,679   | 2748            | 16.8923057(32)       | 94.2     |
| Chandra       | ACIS-S3/CC| 15613   | 2013 Feb 18 | 56,341.12  | 17,093   | 2463            | 16.8923083(30)       | 117.8    |

**Notes.**

\(a\) Background-subtracted counts in the 0.15–2 keV band for XMM-Newton, and the 0.2–4 keV band for Chandra.

\(b\) 1\( \sigma \) error in parentheses.

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**Figure 1.** Pulsar populations on the \((P, \dot{P})\) diagram, including INSs (green squares), magnetars (blue crosses), CCOs (red stars), and Calvera (red triangle). Black dots are isolated pulsars, and circled dots are pulsars in binaries. (Pulsars in globular clusters are excluded as their period derivatives are not entirely intrinsic.) The van den Heuvel (1987) spin-up limit for recycled pulsars corresponds to \(P = \left(\frac{1}{9.11}\right) \times 10^{-13} \text{ s}^{-2}\). The radio pulsar death line \(B/P^2 = 1.7 \times 10^{11} \text{ G s}^{-2}\) of Bhattacharya et al. (1992) is indicated. (A color version of this figure is available in the online journal.)

**Figure 2.** X-ray timing of Calvera using the measurements listed in Table 1. The fitted frequency derivative corresponds to \(P = \left(3.19 \pm 0.08\right) \times 10^{-15}\). Residuals from the linear fit are shown in the lower panel.

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Changes orders of magnitude larger than our uncertainties. A wide binary with a very cool white dwarf and period of order years could possibly accommodate the timing data and optical limit if the distance is large, but such systems are rare. A substellar companion would not be massive enough to account for the period change.

In the absence of clear evidence for orbital motion, we interpret the long-term decrease in frequency as intrinsic to a single NS. Accordingly, we determined the frequency derivative with a \(\chi^2\) fit to the four frequency measurements, with the result that \(\dot{f} = (-9.11 \pm 0.24) \times 10^{-13} \text{ s}^{-2}\). This value is only a factor of \(\approx 2\) smaller than the upper limit determined previously from the two XMM-Newton observations alone (Halpern 2011). The corresponding spin-down properties are \(E = 6.1 \times 10^{33} \text{ erg s}^{-1}, \tau_c = 2.9 \times 10^5 \text{ yr, and } B_x = 4.4 \times 10^{11} \text{ G.}\)

The normalized and background-subtracted pulse profiles of Calvera are shown in Figure 3 for both XMM-Newton and Chandra data. We note the increase in pulsed fraction as a function of X-ray energy. This is especially clear from XMM-Newton, which has much higher throughput at the lowest energies than Chandra.

Spectral fits to the combined Chandra CC-mode data yield results similar to previous observations (Shevchuk et al. 2009;
3. SEARCH FOR $\gamma$-RAYS

Given its high spin-down power and likely proximity, it is surprising that Calvera is not a bright Fermi pulsar. We can place a conservative upper limit of $F_\gamma < 3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ on its $>100$ MeV flux simply from its absence in the 2GFL catalog (Nolan et al. 2012), as this flux is comparable to the weakest cataloged sources in its immediate vicinity. This corresponds to a luminosity upper limit of $L_\gamma < 1.4 \times 10^{35} d_{2}$ kpc erg s$^{-1}$, assuming isotropic. (The adopted upper limit on Calvera’s distance, 2 kpc, will be justified in Section 4.1). In comparison, detected $\gamma$-ray pulsars of similar $E$ typically have $L_\gamma = 10^{34–35}$ erg s$^{-1}$. Next, we make a more sensitive test for $\gamma$-ray emission at the position of Calvera by using the additional Fermi data accumulated since the construction of the 2GFL catalog, and also by searching for pulsations around the known $f$ and $f'$.

To search for $\gamma$-ray point-source emission from Calvera, we retrieved Pass 7 Fermi LAT event data between 2008 August 4 and 2013 July 1 and within $20^\circ$ of the pulsar position.

Zane et al. (2011). Parameters for a power-law plus blackbody fit and a two-blackbody model are listed in Table 2. Even though the power-law plus blackbody is a good fit, XMM-Newton spectra that have better statistics at low energy find that the same model requires $N_H$ to exceed the Galactic value of $2.7 \times 10^{20}$ cm$^{-2}$ by a factor of three (Zane et al. 2011). Therefore, we prefer the purely thermal model, which does not suffer from this problem, but does require two temperatures, i.e., the same number of parameters as the power-law plus blackbody.

### Table 2

| Parameter     | Value $^a$ | Notes |
|---------------|------------|-------|
| Exp. time (s) | 36,772     |       |
| Counts (s$^{-1}$) | 0.138     |       |

#### Power-law plus blackbody model

- $N_H (\text{cm}^{-2})$: $3.7^{+5.8}_{-3.7} \times 10^{20}$
- $\Gamma$: $3.7^{+0.6}_{-0.5}$
- $kT_1 (\text{keV})$: $0.259^{+0.012}_{-0.013}$
- $R_1 (\text{km})$: 0.096
- $F_1 (0.3–10 \text{ keV})$: $1.09 \times 10^{-12}$
- $L_1 (0.3–10 \text{ keV})$: $1.63 \times 10^{31}$
- $\chi^2(\nu)$: 1.004(70)

#### Two-blackbody model

- $N_H (\text{cm}^{-2})$: $<3 \times 10^{20}$
- $kT_1(\text{keV})$: $0.090 \pm 0.006$
- $R_1 (\text{km})$: 0.99
- $kT_2 (\text{keV})$: $0.264 \pm 0.005$
- $R_2 (\text{km})$: 0.11
- $F_2 (0.3–10 \text{ keV})$: $1.07 \times 10^{-12}$
- $L_2 (0.3–10 \text{ keV})$: $1.15 \times 10^{31}$
- $\chi^2(\nu)$: 1.153(70)

**Notes.**

$^a$ Uncertainties are 90% confidence for one interesting parameter.

$^b$ Assuming $d = 300$ pc.

$^c$ Absorbed flux in units of erg cm$^{-2}$ s$^{-1}$.

$^d$ Unabsorbed luminosity in units of erg s$^{-1}$, for $d = 300$ pc.
The analysis was carried out using the Fermi Science Tools\textsuperscript{1} v9r27p1. Following the recommended analysis guidelines from the Fermi Science Support Center, the data were filtered for “source” class events in good time intervals with energies above 100 MeV, zenith angles smaller than 100°, and telescope rocking angles \( \leq 52° \) using the gtselect and gntktime tools.

It is evident from the resulting Fermi LAT counts map (Figure 4, left) that there is no obvious \( \gamma \)-ray source positionally coincident with Calvera. To determine formally whether Calvera is a \( \gamma \)-ray point source, we carried out a binned likelihood analysis with the gtlike tool based on the input counts, exposure, and source maps, livetime cube, and source model generated with the Fermi Science Tools. The input spectral model for the region of interest included contributions from the putative \( \gamma \)-ray pulsar counterpart, all 2FGL catalog sources within 15° of the pulsar, the extragalactic diffuse emission, and the residual instrumental background, jointly modeled using the iso_p7v6source template, and Galactic diffuse emission, modeled with the gal\_2yearp7v6\_v0 map cube.

The first iteration of the likelihood analysis revealed excess emission 2\degree 7 ENE of Calvera’s position that does not appear to be associated with any 2FGL source (see Figure 4). Hence, we added a model source described by a power law at its position, (J2000.0) R.A. = 15\degree 10\(^{m}\) 53\(^{s}\), decl. = +80\degree 05\(^{m}\) 50\(^{s}\) (J2000.0). The likelihood analysis assigned it a test statistic (TS) value of 33.7, corresponding to a significance of \( \approx 5.8\sigma \). This source is \( < 6 \)’ from a radio source with an inverted spectrum at 0.3–8.5 GHz, listed as CRATES J151032.75+80005.3 by Healy et al. (2007), which also has an X-ray counterpart, 1RXS J151026.3+795946, and magnitudes from the Wide-field Infrared Survey Explorer\textsuperscript{2} (Wright et al. 2010), \( W1 = 13.428(24), W2 = 12.384(23), W3 = 9.584(26), W4 = 7.317(67) \), that are typical of \( \gamma \)-ray blazars (Massaro et al. 2012). These blazar properties give us added confidence that the new \( \gamma \)-ray source is real. Its redshift is unknown, although it has a faint optical counterpart (on the Palomar Observatory Sky Survey) that could lead to a measurement.

As appropriate for a pulsar, we model Calvera’s \( \gamma \)-ray spectrum as a power law with an exponential cutoff, of the form \( dN/dE \propto E^{\Gamma} \exp(-E/E_c) \), where \( \Gamma \) is the photon spectral index and \( E_c \) is the cutoff energy. The spectral parameters of the pulsar, the 16 sources within 10°, and the normalization factors of diffuse components were left free in the fit. For sources between 10° and 15° away the spectral parameters were kept fixed.

The likelihood analysis gives a TS (for a definition see Nolan et al. 2012) value of 3.9 for Calvera, which corresponds to only a \( \sim 2\sigma \) detection. The spectral parameters are poorly constrained. The low statistical significance indicates that the addition of a source at Calvera’s position is not warranted by the existing Fermi LAT data, implying that the pulsar is not a \( \gamma \)-ray source. Given the non-detection, to estimate the upper limit on Calvera’s \( \gamma \)-ray flux we followed the procedure used by Romani et al. (2011). In particular, we computed an expected photon index and an exponential cutoff energy using the empirical relations \( \Gamma = -4.1 + 0.156 \log_{10} E \) and \( E_c (\text{GeV}) = -0.45 + 0.71 \log_{10} B_{\text{LC}} \), where \( B_{\text{LC}} \approx 9.3 P^{-5/2} (P/10^{-15})^{1/2} \) G is the magnetic field at the light cylinder. This predicts \( \Gamma = 1.5 \) and \( E_c = 2.6 \) GeV for Calvera. We then repeated the likelihood analysis with Calvera’s \( \Gamma \) and \( E_c \) fixed at these values, while allowing the flux normalization to vary. Based on the resulting value, the UpperLimit Python module from the Fermi Science Tools gives \( < 8.2 \times 10^{-10} \) photons cm\(^{-2} \) s\(^{-1} \), translating to an energy flux of \( < 6.8 \times 10^{-13} \) erg cm\(^{-2} \) s\(^{-1} \) in the 0.1–300 GeV interval. The corresponding upper limit on luminosity, \( L_{\gamma} < 3.3 \times 10^{32} d_{2pc}^2 \text{ erg s}^{-1} \), is illustrated in Figure 5 in comparison with detections of 88 pulsars from the Second Fermi Large Area Telescope Catalog of Gamma-Ray Pulsars (Abdo et al. 2013).

Despite the lack of a \( \gamma \)-ray detection in the image plane, a search for pulsed emission is potentially more sensitive, especially if the signal is sharply peaked. Accordingly, we searched for \( \gamma \)-ray pulsations at the position of Calvera in aperture radii ranging from 1° to 2°, in 0.5 increments, for photons in both the 0.1–300 GeV and 0.3–300 GeV ranges.

\textsuperscript{1} Available at \url{http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html}.
\textsuperscript{2} Data at \url{http://wise2.ipac.caltech.edu/docs/release/allsky/}. 

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\textbf{Figure 4.} Fermi LAT 0.1–300 GeV counts map (left) and likelihood analysis output model map (right). The blue crosses mark the positions of 2FGL catalog point sources, while the diamond marks the position of the source we added to the model, likely identified with CRATES J151032.75+80005.3. The white circle of radius 1° is centered on the X-ray position of Calvera. (A color version of this figure is available in the online journal.)
Lacking a true ephemeris, we searched around the approximately determined spin frequency $f$ and spin-down rate $\dot{f}$. A large grid search is necessitated by the paucity of γ-ray photons, which requires a time step of at least 100 days during which phase coherence is assumed to be maintained. The number of trials was reduced by confining the range of parameters searched to a set of five possible aliases allowed by the close pair of Chandra observations. In each case, conservative $\pm 3\sigma$ ranges in $f$ and $\dot{f}$ were used to cover all plausible values. To characterize the significance of a putative signal, we used $Z^2_\nu$ tests with $\nu = 1, 2, 3,$ and 4. We repeated the entire search using two reasonable time steps: 100 days and 365 days. Finally, to maximize the sensitivity by using all the data, the power spectra from each segment were added incoherently. No significant pulsed emission is detected in the 48 searches for each of the five trial ephemerides that account for the possible aliased X-ray solutions. This outcome is not surprising considering the small number of photons, if any, that can plausibly be attributed to Calvera.

4. DISCUSSION

4.1. Distance and Origin

The distance to Calvera is poorly constrained by X-ray spectra, and is uncertain by an order of magnitude. Upper limits can be derived from the effective area of thermal X-ray emission, or from the conversion of rotational energy to luminosity in the case that the X-rays are powered by rotation. Scaling the values of blackbody radius in Table 2 with distance, a radius of $R_i = 12$ km for the lower temperature component in the two-blackbody model corresponds to a distance upper limit of 3.6 kpc. Smaller distances were derived by Zane et al. (2011) using hydrogen atmospheres fitted to the XMM-Newton spectra, with $N_H$ fixed at the Galactic value, with the result that $d = 1.5\sim 2.3$ kpc. Here we adopt 2 kpc as an upper limit on $d$ because, since soft X-ray pulsations are seen, the star cannot be at uniform temperature and the effective radius of emission must be smaller than $R_{NS}$. We adopt 200 pc as a tentative lower limit because the X-ray column density, which is better measured by the XMM-Newton data of Zane et al. (2011), is comparable to the total Galactic 21 cm value.

At $d = 2$ kpc, the X-ray luminosity of Calvera would be $L_x = 5 \times 10^{32}$ erg s$^{-1}$, a typical value for thermal emission from an NS of its age, $\tau_x = 290$ kyr, and consistent with theoretical NS cooling curves (e.g., Page et al. 2009). Even at 200 pc, the corresponding $L_x = 5 \times 10^{35}$ erg s$^{-1}$ is not unusual, since NS temperatures are falling steeply at this age, particularly those with light-element envelopes. Even some younger NSs, such as RX J0007.0+7303 in the supernova remnant CTA 1, are seen to be this faint (Halpern et al. 2004), which could be the effect of a larger mass. However, the (unmeasured) non-thermal X-ray luminosity of Calvera would be exceptionally small if at $d = 200$ pc, probably of order $10^{-5} \times \dot{E}$, while for most pulsars the ratio $L_x/\dot{E}$ is greater than $10^{-5}$ (Kargaltsev et al. 2012b).

Calvera stands out as the most extreme case of a “young” pulsar at high Galactic latitude, $b = +37^\circ$. Its X-ray properties allow it to be nearby, in the Galactic disk, or far enough to reside in the halo. If in the halo, it was either born there or ejected from the disk at high velocity, $v \approx 1000 \, \text{km s}^{-1}$, where $\varepsilon_{300}$ is its height above the disk in units of 300 pc. This is near the upper limit of observed velocities of pulsars (Hobbs et al. 2005). The ejection scenario implies a proper motion $\mu \; \lesssim \; 10^{-3} \, \text{mas yr}^{-1}$ to have reached latitude $b = +37^\circ$ in $\tau_x = 290$ kyr. To the extent that the true age of a young pulsar is less than its characteristic age, the proper motion could be even larger.

If at a distance of $\sim 2$ kpc, Calvera must have been born in the halo. If its progenitor was a halo star, or a runaway O or B star from the disk, then the proper motion of the NS could be up to a factor of $\sim 3$ smaller than indicated above and oriented in any direction after the random supernova kick. Calvera’s proper motion will be measured by an approved Chandra HRC observation in comparison with the original one from the year 2007 (Rutledge et al. 2008).

4.2. Comparison with PSR J1740+1000

The pulsar whose circumstances most resemble Calvera’s is PSR J1740+1000, a $0.154$ s radio pulsar with $\tau_x = 114$ kyr at $b = +20^\circ$ and $d \approx 1.24$ kpc, for which a halo or runaway progenitor scenario has also been suggested (McLaughlin et al. 2002). The quoted dispersion-measure (DM) distance is from the Australia Telescope National Facility catalogue (Manchester et al. 2005, version 1.47) and is based on the NE2001 Galactic free electron density model of Cordes & Lazio (2002). The X-ray measured column density to PSR J1740+1000 (Kargaltsev et al. 2012a) is consistent with the Galactic 21 cm value. If PSR J1740+1000 was ejected from the Galactic disk, its proper motion would have to be $\sim 590$ mas yr$^{-1}$. However, we can use a pair of existing Chandra observations to rule out this possibility directly. Inspecting ACIS images of PSR J1740+1000 taken in 2001 August (ObsID 1989, 5 ks) and 2010 June (ObsID 11250, 64 ks), its centroid position is (J2000.0) R.A. $= 17^h40^m25^s94$, decl. $= +10^\circ00'05''9$.

http://www.atnf.csiro.au/research/pulsar/psrcat/expert.html
and R.A. = $17^\circ 40^\prime 25.95^\prime\prime$, decl. = $+10^\circ 00^\prime 06^\prime\prime.1$, respectively. Within the nominal Chandra uncertainty of $0.6^\prime\prime$, these positions are indistinguishable from each other and from the radio timing position, R.A. = $17^\circ 40^\prime 25.950(5)$, decl. = $+10^\circ 00^\prime 06^\prime\prime.3(2)$, whose epoch is 2000 April (McLaughlin et al. 2002).

Taking $0.6^\prime\prime$ as an upper limit on the displacement of PSR J1740+1000 over a 10 yr time span, this implies a proper motion of $<$60 mas yr$^{-1}$, or a displacement of $<2^\circ$ since birth, meaning that it was born outside of the disk if the DM distance is correct. Note that this argument is independent of the possible X-ray “tail” of PSR J1740+1000 (Kargaltsev et al. 2008), whose orientation could be interpreted as indicating motion parallel to the Galactic plane. In any case, the tail may not be real, because the 64 ks Chandra image of PSR J1740+1000 from 2010 does not clearly show it. Curiously, PSR J1740+1000 is also undetected in $\gamma$-rays by Fermi, as we discuss in Section 4.4.

4.3. Classification of Calvera

The place of Calvera among the families of NSs is still not clear despite our measurement of its spin and spectral properties. Of the previous hypotheses, we can now rule out only a mildly recycled pulsar, as Calvera lies far above the spin-up limit in Figure 1. Its dipole field of $4.4 \times 10^{11}$ G is on the low end for ordinary rotation-powered pulsars of the same characteristic age, but is not unprecedented. It is difficult to characterize its true (thermal) age using theoretical cooling curves, first, because such curves vary, depending on several unknown parameters. Second, its X-ray emitting hot spot(s) do not represent the full surface area of the NS. Third, it is entirely possible that some of the thermal emission is due to polar cap heating by backflowing magnetospheric particles (Harding & Muslimov 2001, 2002). A typical ratio $L_\gamma/E \sim 10^{-3}$ attributed to this process is seen in thermally emitting millisecond pulsars, and Calvera’s ratio is no larger than this.

Even at the adopted upper-bound distance of $\sim 2$ kpc, spin-down power could explain all of Calvera’s emission. The pulsed light curves exhibit a pronounced increase in pulsed fraction with increasing energy (see Figure 3), which is characteristic of localized heating or enhanced conduction from the interior, either of which are expected at the magnetic poles of an NS. Preliminary modeling suggests that the pulse profiles as a function of energy can be fitted assuming two roughly antipodal hot spots differing in temperature by a factor of two. A weak, non-thermal spectral component may be present above 2 keV, which is weak enough so that only its pulsed luminosity has been measured. Nevertheless, it is more luminous than Calvera.

If Calvera is one of the nearest pulsars, at $d \sim 200$ pc, then its $\gamma$-ray luminosity is $<5.3 \times 10^{39}$ erg s$^{-1}$. This is far below any other pulsar of comparable $E$ that it could logically be taken as an argument against such a small distance. However, we are not certain what the limits are on possible beaming corrections for $\gamma$-ray pulsars. In order to explain $\gamma$-ray-weak pulsars such as PSR J1740+1000, Romani et al. (2011) favored an interpretation in which an aligned rotator, with the observer close to the rotation axis, would direct its outer-gap $\gamma$-ray emission away from the observer. But Calvera is not likely to be an aligned rotator given its large X-ray pulsed fraction, $\sim 30\%$ above 1 keV (Figure 3). Neither is PSR J1740+1000 likely to be an aligned rotator, as its thermal X-ray emission also has a pulsated fraction of $\sim 30\%$ (Kargaltsev et al. 2012a). Furthermore, it is difficult to understand the lack of radio pulsations from Calvera if it is an aligned rotator unless it is intrinsically radio silent. The absence of both radio and $\gamma$-ray emission from Calvera must imply a strong constraint on the beaming patterns and creation of high-energy particles in pulsars. Now having two energetic pulsars at high Galactic latitude with no $\gamma$-ray emission to faint limits, we wonder if other undetected pulsars in the Galactic plane could be similarly weak, while source confusion and diffuse emission prevent such low upper limits from being established for them.

5. CONCLUSIONS

More than 3 yr after 59 ms X-ray pulsations were discovered from Calvera, we obtained new timing observations with Chandra that show its frequency to have changed, corresponding to $f = (-9.11 \pm 0.24) \times 10^{-13}$ s$^{-2}$. Interpreting this as the dipole spin-down of a single NS, its derived properties are

Nevertheless, independent of the discovery of Calvera, a theory for CCOs has been developed that involves burial of a typical NS magnetic field ($\sim 10^{12}$ G) by prompt fallback of a small amount of supernova ejecta, followed by diffusive regrowth of the same field on a timescale of $\sim 10^4$ yr (Ho 2011; Viganò & Pons 2012; Bernal et al. 2013). Magnetic field growth has long been suggested as a reason why pulsar braking indices are all less than the dipole value of 3. In this picture, CCOs would be in a phase of rapid field growth, with large negative braking index, and their immediate descendants would lie directly above them on the $(P, \dot{P})$ diagram. The possibility that Calvera, or almost any radio pulsar for that matter, was once a CCO, cannot therefore be ruled out. Such a scenario, in which CCOs quickly join the ordinary radio pulsar population, carries the added benefit of not requiring yet another family of NSs to exist that could explain the data.
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E = 6.1 × 10^{35} \text{ erg s}^{-1}, \tau_c = 290 \text{ kyr}, and B_p = 4.4 \times 10^{11} \text{ G}.

These make Calvera an energetic, young pulsar with a magnetic field toward the low end of the distribution and unusual for its absence of γ-ray emission.

We performed image likelihood and timing searches on almost 5 yr of Fermi data, with a resulting upper limit of <8.2 \times 10^{-10} \text{ photons cm}^{-2} \text{ s}^{-1}, or energy flux <6.8 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} above 100 \text{ MeV}, a faint limit that is made possible by Calvera’s location at high Galactic latitude, +37°.

How extreme this non-detection is depends on the poorly known distance. Since X-ray spectral fits have an absorbing column density greater than or equal to the Galactic value, we estimate a lower limit on d > 200 pc. An upper limit of ~2 kpc can be set by requiring the thermal X-ray emitting area, which dominates the X-ray luminosity, to be less than the surface area of a 12 km radius NS. The equivalent upper limit on γ-ray luminosity is L_γ < 3.3 \times 10^{32} d_{200}^2 \text{ erg s}^{-1}, smaller than all γ-ray pulsars of similar E. If Calvera were as close as 200 pc, the absence of both radio and γ-ray luminosity would be extraordinary and challenging for existing models of pulsar acceleration zones and beaming, especially since Calvera has substantial X-ray pulse modulation. The combination of these properties is difficult to accommodate in an aligned rotator, or any other geometry.

The radio pulsar PSR J1740+1000 bears some resemblance to Calvera in that it is a young, energetic pulsar at high Galactic latitude. Instead, its progenitor could have been a runaway O or B star. We will soon assess Calvera’s proper motion with an upcoming Chandra HRC observation.

It had been speculated that Calvera could be an orphaned CCO, a descendant of the weakly magnetized X-ray pulsars that fall unexpectedly in a sparsely occupied region of (P, P) space. Even though its dipole magnetic field is larger than that of the CCO pulsars, Calvera could be following the track predicted by the theory of field burial, with a magnetic field that was initially submerged by supernova debris, but is rapidly reemerging and approaching normal strength. In this theory, many ordinary radio pulsars may be the orphaned CCOs, which could be revealed by an excess of thermal X-ray luminosity with respect to their spin-down ages.

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