DEEP OPTICAL OBSERVATIONS OF UNUSUAL NEUTRON STAR CALVERA WITH THE GTC

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ABSTRACT

Calvera is an unusual, isolated neutron star with a pure thermal X-ray spectrum typical of central compact objects in supernova remnants. On the other hand, its rotation period and spin-down rate are typical of ordinary rotation-powered pulsars. It was discovered and studied through X-rays, and has not yet been detected in other spectral domains. We present deep optical imaging of the Calvera field, obtained with the Gran Telescopio Canarias, in the g′ and i′ bands. Within the vicinity of ≈1″ of Calvera, we detected two point-like objects that were invisible at previous shallow observations. However, accurate astrometry showed that neither of them can be identified with the pulsar. We put new upper limits of g′ > 27.87 and i′ > 26.84 on its optical brightness. We also reanalyzed all available archival X-ray data on Calvera. Comparison of the Calvera thermal emission parameters and upper limits on optical and non-thermal X-ray emission with respective data on rotation-powered pulsars shows that Calvera might belong to the class of ordinary middle-aged pulsars, if we assume that its distance is in the range of 1.5–5 kpc.

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

1. INTRODUCTION

The high Galactic latitude (b ≈ +37°) compact source 1RXS J141256.0+792204, in the ROSAT All-Sky Survey, was proposed as a neutron star (NS) candidate by Rutledge et al. (2008), based on its high X-ray to optical flux ratio. It was the first plausible isolated NS (INS) candidate found in the survey after the identification of seven purely thermal-emitting, radio-quiet INSs dubbed “The Magnificent Seven.” This led Rutledge et al. (2008) to nickname 1RXS J141256.0+792204 as “Calvera,” after a character in that film. Subsequent observations confirmed the NS nature of Calvera, and revealed unusual properties that make it difficult to attribute the source to any specific class of NS (for details, see Zane et al. 2011 and Halpern et al. 2013).

The initial idea that Calvera could be a new member of the Magnificent Seven family was ruled out by X-ray timing observations. Using XMM-Newton, Zane et al. (2011) discovered X-ray pulsations with the period P ≈ 59 ms. Chandra observations then allowed Halpern et al. (2013) to measure, and later to refine (Halpern & Gotthelf 2015), the spin-down rate with the period derivative δP ≈ 3.2 × 10−13 s−1, yielding a spin-down luminosity of $E ≈ 6.1 \times 10^{35}$ erg s−1, characteristic age $\tau \approx 290$ kyr, and dipole magnetic field $B \approx 4.4 \times 10^{11}$ G. These values are drastically different from those of Magnificent Seven NSs, which are much less energetic ($\dot{E} \sim 10^{30–32}$ erg s−1), slower-rotating ($P \sim 1–10$ s), older ($\tau \sim 1$ Myr), and more highly magnetized ($B \sim 10^{13}$ G) INSs (e.g., Haberl 2007; Kaplan et al. 2011).

Alternative interpretation of Calvera as an ordinary rotation-powered pulsar (RPP) is also challenging. Deep searches failed to detect it through radio emissions (Hessels et al. 2007; Zane et al. 2011), and no evident non-thermal emission component that would be expected for such an energetic pulsar was found in X-rays (Zane et al. 2011; Halpern et al. 2013). Neither steady nor pulsed signals were detected, with Fermi, in $\gamma$-rays (Halpern 2011; Halpern et al. 2013). The out-of-beam scenario is frequently considered for the non-detection of a narrow-beamed pulsar radio emission. However, it is hardly plausible in the high energy bands where pulsar beams are much wider. The non-thermal emission component can be suppressed for aligned magnetic rotators. However, Calvera shows a high X-ray pulsed fraction of $\approx 18\%$ (Zane et al. 2011) excluding this possibility. It was also speculated that Calvera could be a descendant of a central compact object—one of the weakly magnetized ($<10^{11}$ G), thermally emitting NSs observed in supernova remnants—whose magnetic field was initially buried in the NS crust by a prompt fallback of the parent supernova ejecta, and now is emerging back to the surface (Gotthelf et al. 2013; Halpern & Gotthelf 2015).

The proper motion of Calvera, $\mu = 69 \pm 26$ mas yr$^{-1}$, was recently measured with Chandra by Halpern & Gotthelf (2015), showing the proper motion vector pointing outside of the Galactic plane. The authors argue that Calvera could have been born inside the Galactic disk, and now is at a distance of $\lesssim 0.3$ kpc with transverse velocity of $\lesssim 120$ km s$^{-1}$. However, they did not find any suitable birthplace for Calvera within the disk. Moreover, if Calvera is at a distance of $\lesssim 0.3$ kpc, it is several orders of magnitude under-luminous in $\gamma$-rays, as compared to other pulsars with similar $\dot{E}$ (Halpern et al. 2013). On the other hand, as it was noted by Posselt et al. (2008) and Halpern et al. (2013), Calvera could be much more distant if it was born in the Galactic halo or its progenitor was a runaway star.

Thus, despite the intensive radio, X-ray, and $\gamma$-ray studies, Calvera remains a puzzling NS. Its distance, classification, and evolution status are still uncertain and need further multi-wavelength studies. Its high Galactic latitude—and hence, low absorption column density—make it a promising target for
optical observations. Until now, the Calvera field was observed with the Gemini-N telescope in the g band, but no optical counterpart of Calvera was found down to a brightness limit $g \geq 26.3$ (Rutledge et al. 2008).

We report new, much deeper optical imaging of the Calvera field in the g' and i' bands, performed with the Gran Telescopio Canarias (GTC). We discovered a faint red object ($g' = 26.22$ and $i' = 24.17$) located at $\sim 0''7$ of the Calvera position. Accurate astrometry of the optical and X-ray images shows that the object is unlikely to be an optical counterpart of Calvera. We put upper limits on the Calvera optical fluxes. We also re-analyse all the available X-ray data and argue that the thermal X-ray spectrum of Calvera can be described by the magnetized hydrogen atmosphere model with either a uniform or non-uniform temperature distribution (NSMAX model; Ho et al. 2008), corresponding to the emission from the bulk of the NS surface located at a distance of 1.5–5 kpc. We also confirm previous claims of the presence of a spectral absorption feature in the X-ray spectrum of Calvera. Overview of the optical observations, data reduction, and archival data used in the analysis is presented in Section 2. Analysis of the optical data and search for an optical counterpart of Calvera are given in Sections 3–5. Spectral analysis of the X-ray data is reported in Section 6. We discuss implications of our results in Section 7.

2. OBSERVATIONS OF CALVERA AND ARCHIVAL DATA

2.1. GTC Observations and Data Reduction and Calibration

Our observations of the pulsar field were carried out in the Sloan g' and i' bands, with the Optical System for Imaging and low-intermediate Resolution Integrated Spectroscopy (OSIRIS) at the GTC, in a queue-scheduled service mode during 2014 April and June. With an image scale of 0''254 pixel$^{-1}$ (2 × 2 binning) and unvignetted field size of 7'8 × 7'8 available for the OSIRIS detector—consisting of a mosaic of two CCDs—we obtained three sets of dithered exposures. Calvera was exposed on CCD2. The observing conditions were clear, with stellar flux variations of less than 4%, and seeing varied from 0''7 to 1''1 (see Table 1).

Standard data reduction, including bias subtraction, flat-fielding, cosmic-ray removal, and bad pixel correction was performed with IRAF and MIDAS tools. Because the images were mainly obtained during a gray time, they were partially contaminated by a nonuniform background caused by a small inclination of the OSIRIS detector filter wheels. In order to eliminate the contamination, we performed illumination corrections for each observational set. Finally, using a set of unsaturated stars, we aligned all the individual exposures in each band to the best ones obtained at the highest-quality seeing conditions. The resulting combined images have mean seeing of 0''93 and 0''96, mean airmasses of 1.62 and 1.77, and total integration times of 7.55 and 18.09 ks, for the g' and i' bands, respectively.

For photometric calibrations, we used photometric standards SA 112 805 and PG 1047+003a for the g' band, and SA 104 428 for the i' band, which were observed the same nights as our target. The atmospheric extinction coefficients $k_g = 0.15 \pm 0.02$ and $k_i = 0.04 \pm 0.01$ were taken from 2014 OSIRIS/GTC broadband imaging calibration notes. The derived magnitude zero-points for g' and i' images in CCD2, where our target was exposed, are $28^{\pi}79 \pm 0^{\pi}04$ and $28^{\pi}71 \pm 0^{\pi}04$, respectively. The uncertainties include the statistical measurement errors, $\approx 4\%$ stellar flux variations from exposure to exposure of the target field, the atmospheric extinction coefficient uncertainties, and, in the case of the g'-band, the zero-point variations from night to night. The g'-band zero-point is fully consistent with the mean values for photometric/clear nights presented in the OSIRIS/GTC calibration notes, whereas the i' zero-point is marginally, by 1σ, lower than the respective mean values, which may indicate that the i' observations were slightly affected by dust in the atmosphere—as is typical for the GTC site during summertime. Here, we ignore color terms in the instrumental to AB magnitude transformations. Their contributions were evaluated to be always within the estimated error budgets, and did not affect our results.

2.2. The Gemini-North Archival Data

In our analysis, we also used the archival Gemini-North Multiobject Spectrograph (GMOS-N) observations obtained in 2006 December, in the g band, with an exposure of 4 × 600 s (Rutledge et al. 2008). Four dithered exposures were retrieved from the Gemini archive, and reduced using the IRAF GMOS pipeline and official calibration products (bias, flats, bad pixel map, etc.). The image scale and unvignetted field size are 0''145 pixel$^{-1}$ and 5'4 × 5'4, respectively. Calvera was exposed on the central CCD of the three GMOS. The mean seeing and airmass on the combined image are 1''3 and 2.3, respectively.

2.3. Chandra and XMM-Newton Archival Data

For the X-ray spectral analysis, we used archival Chandra Advanced CCD Imaging Spectrometer (ACIS) and XMM-Newton European Photon Imaging Camera (EPIC) data (Table 2). The XMM-Newton data were processed with the XMM-SAS v.13.5.0 software. We selected single and double pixel events (PATTERN ≤ 4) for the EPIC-pn, and single-to-quadruple pixel events (PATTERN ≤ 12) for the EPIC-MOS1 data. We did not use the MOS2 data for spectral analysis because MOS2 was in timing mode, which is not accurately calibrated for spectral analysis. We removed periods of background flares using 10–12 keV and 12–14 keV light curves for the MOS1 and pn data, respectively. Using the evselect tool, we extracted spectra from the 30'' aperture centered at the Calvera position that encapsulates most of the Calvera emission. We used SAS tasks rmfgen and arfgen to generate redistribution matrix and ancillary response files.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Date & Band & Exposure (s) & Airmass & Seeing (arcsec) \\
\hline
2014 Apr 04 & g' & 4 × 686 & 1.59–1.62 & 0.9–1.1 \\
2014 Jun 04 & i' & 35 × 134 & 1.64–1.79 & 0.7–1.0 \\
2014 Jun 26 & g' & 7 × 686 & 1.58–1.63 & 0.7–0.9 \\
\hline
\end{tabular}
\caption{Log of the GTC/OSIRIS Observations of the Calvera Field}
\end{table}
respectively. The resulting exposure times and number of source counts (in the 0.3–7.0 keV range) after background subtraction are listed in Table 2. The total number of source counts obtained with XMM-Newton in the 0.3–7.0 keV range is 18979.

In the Chandra spectral observation, Calvera was exposed on the ACIS-S3 CCD chip. We reprocessed these data using the CIAO v.4.7 chandra_repro tool with CALDB v.4.6.9. For the data obtained in the VFAINT mode (ObsIDs 9141), we extracted the pulsar photons from the 1.5 aperture centered at the Calvera position with the CIAO specextract tool. For the data obtained in the CC mode (ObsIDs 13788 and 15613), we extracted spectra from the five columns near the pulsar position. The total number of source counts obtained with Chandra in the 0.3–7.0 keV range is 9713 (see Table 2). For the XMM-Newton and Chandra data, background was taken from regions free from any sources. All spectra were grouped to ensure at least 25 counts in each energy bin. For the X-ray image analysis, we used the archival Chandra high-resolution camera data, obtained with the micro-channel plate imaging detector I (HRC-I) in 2014 April—almost simultaneously with the GTC data (Halpern & Gotthelf 2015). HRC-I provides subarcsecond resolution data that are useful for optical counterpart identification. The data were reprocessed with the chandra_repro tool, and image corrected for the exposure map was then created.

3. OPTICAL AND X-RAY ASTROMETRY

Precise astrometric referencing between the Chandra/HRC-I and GTC images is crucial to search for the Calvera optical counterpart. The only appropriate reference source for that is USNO-B1.0 1693–0051234, the X-ray counterpart (CXOU J141259.4+791958) of which is located 2′ southward of Calvera (Rutledge et al. 2008). Unfortunately, it is strongly saturated in GTC images. The same is true for other bright astrometric standards in the field. There are also some geometric distortions in GTC images toward CCD boundaries outside a few arcminutes from the Calvera position. Therefore, we used the Gemini image as a proxy to obtain the astrometric solution, because it has negligible geometric distortions and the reference source and most other standards are unsaturated. Using twenty unsaturated stars around Calvera from the USNO-B1 astrometric catalog and the IRAF ccmap task, we referenced the Gemini image to the World Coordinate System (WCS) with formal rms uncertainties of the astrometric fit ΔR.A. ≈ 0″0.11 and Δdecl. ≈ 0″0.13. This is consistent with the nominal catalog uncertainty of ≈0″0.2, and results in a conservative 1σ WCS referencing uncertainty of 0″0.23 for the whole Gemini image. We then performed referencing of the central part of the GTC g′ image—containing Calvera—to the Gemini image. We selected nine point-like unsaturated secondary astrometric standards that are well-detected in both images, within ∼2′ of the Calvera position. The rms reference uncertainties of 0″0.092 and 0″0.044 for R.A. and decl., respectively, yielded a 1σ WCS referencing uncertainty of ≈0″0.24 for this region. The GTC i′ image was then tied to the g′ image, with uncertainties of ΔR.A. = 0″0.042 and Δdecl. = 0″0.055.

The referencing of the HRC-I image to the Gemini one is not straightforward, because only one reference source is available. Fortunately, the source USNO-B1.0 1693–0051234 is extragalactic, and its proper motion is negligible (Halpern & Gotthelf 2015). Comparing the WCS-referenced Gemini image to the HRC-I image with nominal Chandra WCS referencing, we found a significant offset of 0″0.096 between the optical and X-ray coordinates of the reference source, which is consistent with what was reported by Halpern & Gotthelf (2015). The offset is within the nominal 90% astrometric uncertainty of the HRC-I image of 0″6; however, fine-tuning of Gemini-HRC-I referencing is possible. Following Halpern & Gotthelf (2015), we shifted the HRC-I image, eliminating the offset. The centroid positions of the reference source in the HRC-I and Gemini images have uncertainties of 0″0.025 and 0″0.005, respectively, for both coordinates. Therefore, the image shift is determined with an accuracy of 0″0.025.

In the HRC-I observations, the reference source was placed on the optical axis, to ensure the most precise referencing (Halpern & Gotthelf 2015); therefore, Calvera was observed 2′ off-axis. For the off-axis sources, there are additional reference errors related to the plate rotation and scale, which cannot be accounted for with only one reference source. The Chandra roll angle uncertainty is ≈25″; hence, it results in a systematic error of 0″015 for a source 2′ off-axis.8 We examined possible nonlinearity of the HRC plate scale using some archival data with sufficient numbers of reference sources, and found that it introduces ≤0″0.05 astrometric error within 2′ of the optical axis. Details of the analysis are given in the Appendix. We took these values into account to obtain the resulting uncertainty of the HRC-I referencing. Combining the referencing uncertainties with the HRC-I Calvera centroid position uncertainty of

Table 2
X-Ray Spectral Observations of Calvera

| DateObs        | Exp. (s) | Inst.   | Mission       | ObsID         | ObsMode | Observer | Phot. |
|----------------|---------|---------|---------------|---------------|---------|----------|-------|
| 2009 Aug 31    | 11351   | EPIC-pn | XMM-Newton    | 0601180101    | SW      | S. Zane  | 5958  |
| 2009 Oct 10    | 19477   | EPIC-pn | XMM-Newton    | 0601180201    | SW      | S. Zane  | 9846  |
| 2009 Aug 31    | 6273    | EPIC-MOS1| XMM-Newton    | 0601180101    | FW      | S. Zane  | 694   |
| 2009 Oct 10    | 22469   | EPIC-MOS1| XMM-Newton    | 0601180201    | FW      | S. Zane  | 2481  |
| 2013 Feb 18    | 17093   | ACIS-S3 | Chandra       | 15613         | CC      | J. Halpern | 2429  |
| 2013 Feb 12    | 19679   | ACIS-S3 | Chandra       | 13788         | CC      | J. Halpern | 2675  |
| 2008 Apr 08    | 26430   | ACIS-S3 | Chandra       | 9141          | VFAINT  | D. Fox   | 4609  |

Note.
6 Number of source counts in the 0.3–7.0 keV range.

8 http://cxc.harvard.edu/cal/ASPECT/roll_accuracy.html

9 ObsID 15806, exposure ≈30 ks, PI J. Halpern.
0\textdegree{}04, we find that its position can be localized on the Gemini image with a 1\textsigma{} uncertainty of 0\textdegree{}07.

Accounting for all the uncertainties, the 1\textsigma{} accuracy of WCS referencing of the HRC-I image within 2\textarcmin{} of the optical axis is 0\textdegree{}24 for both coordinates. The same accuracy holds for WCS referencing of the GTC $g'$- and $i'$-image fragments containing 2\textarcmin{} vicinity of Calvera. The resulting X-ray position of Calvera is shown in Table 3. The reference source USNO-B1.0 1693−0051234 position in our optical images is R.A. = 14:12:59.42(8) and decl. = +79:19:58.80(24). These positions are consistent, within uncertainties, with those reported by Halpern & Gotthelf (2015), providing independent confirmation of their results. They used a similar approach, albeit with the MDM Observatory 2.4 m Hiltner telescope $R$-band image of the field.

### 4. SEARCHING FOR THE CALVERA OPTICAL COUNTERPART

The $g'$-band images of the Calvera field are shown in the top panels in Figure 1. The Calvera X-ray position is marked by the cross. The nearby background optical objects A, B, and C are noted following Rutledge et al. (2008); D and E mark new sources detected with the GTC, with signal-to-noise ratio (S/N) >10. Both D and E are well-resolved in the $g'$ band, whereas they are blended in the $i'$ image. Positions of all these sources are shown in Table 3. As seen, object E is the closest source to Calvera, which projects onto the northwest wing of the spatial profile of object E. Therefore, precise measurement of the offset between them is important to verify whether E can be associated with the pulsar.

The immediate vicinity of Calvera, which includes sources A, D, and E, is enlarged in the bottom panels of Figure 1. The positions of sources E and D were measured with the point-spread function (PSF) fit in each of GTC images, using IRAF/daophot/nstar task. The PSFs were generated using the IRAF/daophot/psf task for an eleven-pixel radius, where the bright isolated unsaturated stars selected for the PSF construction merge with the background. An optimal PSF fit radius was chosen to be about three pixels, in accordance with seeing conditions.

To estimate the position uncertainties, we performed Monte Carlo simulations of synthetic data sets. That is, using the PSF model, we simulated synthetic images of sources A, E, and D, assuming Poisson distribution of total brightness for each source. The background contribution for each pixel was drawn from the Poisson distribution, based on the respective pixel value from the initial IRAF/daophot/nstar fit residual image. In this way, we account for the possible background variations over the image. The uncertainties were then derived from the distribution of sources positions measured on the synthetic images. The resulting 1\textsigma{} uncertainties are $\lesssim$0\textdegree{}03 and $\lesssim$0\textdegree{}05 for the $g'$ and $i'$ images, respectively—consistent with estimates given by the relation by Bobroff (1986) for specific seeing and S/N values. The 90\% uncertainties of $E$ and $D$ positions are shown by white ellipses in the bottom panels of Figure 1. The positions of $D$ and $E$ in both bands are consistent within statistical and $i' - g'$ referencing uncertainties.

Black ellipses in the bottom panels of Figure 1 show the 90\% uncertainties of the Calvera HRC-I position, referenced to the GTC images. The position uncertainties are combined from the 0\textdegree{}07 uncertainty of the HRC-I Calvera position as referenced to the Gemini image, the Gemini–GTC referencing uncertainty (A.R.A. = 0\textdegree{}092 and Ddecl. = 0\textdegree{}044), and, for the $i'$ image, the $i' - g'$ transformation accuracy ($\Delta$R.A. = 0\textdegree{}042 and $\Delta$Ddecl. = 0\textdegree{}055). The resulting sizes of the ellipses are 0\textdegree{}24 × 0\textdegree{}17 and 0\textdegree{}26 × 0\textdegree{}19 for $g'$- and $i'$-band images, respectively. As seen, source $E$ can hardly be an optical counterpart of the Calvera pulsar. Its offset from the Calvera position is 0\textdegree{}067 ± 0\textdegree{}015, which corresponds to $\approx$4.5\textsigma{} significance—or 5 × 10$^{-5}$ probability of coincidence, according to the Rayleigh distribution.

### 5. PHOTOMETRY OF THE GTC IMAGES

Because no reliable optical counterpart of Calvera was found, only an upper limit on its optical flux can be placed. In the source-free regions near the Calvera position in the GTC images, the 3\textsigma{} point-source detection limits are $g'$ > 27.93 and $i'$ > 26.84. However, Calvera is located in the wings of source $E$, which is also blended with source $D$. Therefore, PSF photometry is needed to robustly estimate Calvera brightness upper limits. We performed PSF photometry, using the IRAF/daophot allstar task, with a PSF fit radius of three pixels. Annullus and damnus of 11 and 10 pixels, respectively, were typically used to extract local backgrounds. Using aperture photometry for a large set of field stars, we checked that, in our data, the allstar task does not result in a biased PSF photometry. Aperture corrections were estimated based on the photometry of bright unsaturated field stars and photometric standards, using aperture radii up to 20\textarcmin{}.

For the $g'$ band, the correction was $0.45\pm0.01$, whereas for the $i'$ band, which had a worse seeing, it was $0.60\pm0.01$. The magnitude errors were estimated, accounting for the statistical measurement errors, a magnitude dispersion in the star iterative subtraction process within the allstar task, calibration zero-points, atmospheric coefficient, and aperture correction uncertainties. The PSF subtraction of stellar-like sources $D$ and $E$ is perfect, allowing for a reliable Calvera upper limit estimate. Calvera brightness 3\textsigma{} upper limits estimated using background standard deviations at its positions in the star-subtracted images are $g'$ > 27.87 and $i'$ > 26.89. Within the zero-point and aperture correction uncertainties, these values are compatible with the upper limits given above, for a wider region free of any optical source. To keep our estimates conservative, we accepted the brightest of the limits obtained in each band, i.e., $g'$ > 27.87, $i'$ > 26.84. The photometry results for sources

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| Source | R.A. (J2000) | Decl. (J2000) | $g'$ (mag) | $i'$ (mag) |
|-------|-------------|-------------|-----------|-----------|
| A     | 14:12:56.608 | +79:22:04:17(24) | 24.71(4) | 24.20(11) |
| B     | 14:12:57.868 | +79:22:08:77(24) | 25.17(3) | 24.53(5)  |
| C     | 14:12:57.976 | +79:21:59:98(24) | 25.47(6) | 24.30(5)  |
| D     | 14:12:56.276 | +79:22:02:68(24) | 26.10(5) | 25.37(13) |
| E     | 14:12:55.938 | +79:22:03:16(24) | 26.22(6) | 24.17(11) |
| Calvera | 14:12:55.828 | +79:22:03:73(24) | $\geq$27.87 | $\geq$26.84 |

Note. Measured magnitudes and positions of point-like optical sources, detected in the Calvera vicinity and labeled in Figure 1, as well as the Calvera 3\textsigma{} brightness upper limits and X-ray position. Numbers in brackets are 1\textsigma{} uncertainties, referring to the last significant digits quoted.
$A$–$E$ are summarized in Table 3. In the $g'$ band, $D$ and $E$ have similar magnitudes, whereas $E$ becomes significantly brighter than $D$ in the $i'$ band. For source $A$, our result in the $g'$ band is consistent, within uncertainties, with the estimates of Rutledge et al. (2008) based on a calibration using 10 USNO stars in the field. On the other hand, the brightnesses of fainter $B$ and $C$ sources were significantly underestimated in their work, by a value of $\sim 0.4$, probably due to incorrect aperture correction. According to Table 3, object $E$ is a magnitude redder than other sources. This serves as an additional argument against $E$ being the Calvera optical counterpart, because most pulsars are blue objects in the optical band.

6. X-RAY SPECTRAL ANALYSIS

Below, we consider only the phase-averaged X-ray spectra. Previous analyses of the X-ray data showed that any one-component model (absorbed) cannot satisfactorily describe the spectrum of Calvera (Zane et al. 2011; Halpern et al. 2013). Models with a non-thermal component are excluded, because they require an absorption that is several times the Galactic total, in the direction of Calvera, to fit the soft part of the spectrum in XMM-Newton data (Zane et al. 2011). Thus, the soft part of the Calvera spectrum is supposed to be thermal. Halpern et al. (2013) preferred a model of two hot spots with blackbody spectra ($2BB$) that fit the phase-averaged spectrum and can explain the dependence on photon energy for the pulsed fraction and pulse shape. Zane et al. (2011) showed that the phase-averaged spectrum can be also described by the sum of two hydrogen atmosphere models NSA (Pavlov et al. 1995; Zavlin et al. 1996).

Zane et al. (2011) examined the phase-averaged spectra for the presence of an absorption feature. They found that, when multiplying the two-component thermal model by an absorption edge, the fit improvement is statistically significant. In addition, they showed that the fit is also acceptable for the NSA model with the absorption edge. The presumed presence of an emission line at $\sim 0.5$ keV was pointed out earlier by Shevchuk et al. (2009), based on analysis of the Chandra/ASIS-S data, but the line significance was inconclusive.

We considered various atmosphere models, and found that spectra can be described by a one-component magnetized
hydrogen atmosphere model NSMAX (Ho et al. 2008) that has not yet been applied to the Calvera spectra. Therefore, we focus on this particular model in our analysis. It has certain advantages over the older NSA model. In particular, the NSMAX model accounts for the effects of partial ionization in the opacities of the atmosphere. Moreover, there are publicly available NSMAX models that incorporate smooth (dipole) inhomogeneities of the surface temperature and the magnetic field over the NS surface.

The XMM-Newton data in the 0.3–7 keV range and the Chandra data in the 0.5–7 keV range were fitted simultaneously. For the spectral fitting, we used the Xspec spectral fitting package v.12.9.0 (Arnaud 1996), connected to the Python-based Markov Chain Monte Carlo (MCMC) package emcee (Foreman-Mackey et al. 2013) through the PyXspec Python front-end to Xspec. This approach allowed us to effectively sample the posterior distribution and, in particular, to obtain the fit quality and uncertainties of parameters.

In the upper rows of Table 4, we show the best-fit parameters for three models from the NSMAX series, 1200, 123190, and 123100. The parameters are the hydrogen column density $N_H$, the NS radius to distance ratio $R/D$, and effective temperature as seen by a distant observer $T^e$. The model also depends on the gravitational redshift at the NS surface, but because it was not actually constrained from the fit, we just marginalized posterior distributions over it. The interstellar absorption is accounted for by the TBABS model, with abundances from Wilms et al. (2000). NSMAX model 1200 assumes the constant radial magnetic field of $10^{12}$ G, whereas the models 123100 and 123190 account, in a particular way, for the dipole variations of the magnetic field ($B = 10^{12}$ G at the magnetic equator) and the temperature over the surface (Ho et al. 2008). For NSMAX model 123100, the NS is assumed to be viewed from the magnetic pole, whereas for NSMAX model 123190, the star is viewed in the orthogonal direction. In order to account for the cross-calibration uncertainties between the XMM-Newton pn, MOS1, and Chandra detectors¹⁰, we let $R/D$ vary independently. The parameter uncertainties in Table 4 are 90% highest posterior density (HPD) credible intervals, derived from the marginalized posterior distributions of respective parameters (e.g., Protassov et al. 2002; Gelman et al. 2003). For $R/D$, we give the weighted average value with uncertainties accounting for the statistical and cross-calibration systematic errors.

In addition to traditional inspection of the $\chi^2$ value given in the last column in Table 4, we assessed the goodness-of-fit test by means of the posterior predictive check (Gelman et al. 2003). We found that each of the models in Table 4 fit the data equally well. The spectrum and best-fit residuals are shown in the left panel of Figure 2, for NSMAX model 1200.

It can be seen that a single-component NSMAX 1200 fit is good, but there is still a wavy pattern in the fit residuals between 0.4 and 1.0 keV, with a dip at about 0.7 keV, that probably points to the presence of a spectral feature. The same wavy pattern is seen for other models, as well. To test for the absorption feature, we multiplied all models by the Gaussian absorption profile (GABS) and fit these models to the data. The best-fit parameters are presented in the lower rows of Table 4, and the best-fit NSMAX(1200)×GABS model is compared with data in the right panel of Figure 2. In addition to parameters of the NSMAX model, there are also line center $E_0$, full width at half maximum (FWHM), and the equivalent width (EW). In Figure 3, we also show marginal posterior distributions for the NSMAX(1200)×GABS model parameters. It can be seen that the line parameters are well-constrained, from the fit.

As seen from Table 4, multiplying each of three models by the Bayesian line with its center at about 0.7 keV improves fit statistics. The $F$-test value is 19.6 (for model NSMAX 1200), which corresponds to a probability of $2.7 \times 10^{-12}$, according to the $F$-distribution. This favors the presence of a line. However, it is not correct to use the $F$-distribution to test for a presence of spectral lines (see, e.g., Protassov et al. 2002). Therefore, we utilized the method of posterior predictive $p$-values, as recommended by Protassov et al. (2002). In brief, we simulated spectra under the null model (model NSMAX, in our case) taking parameters from the corresponding posterior distribution, fit them by the null model and an alternative model (in our case, the null model multiplied by GABS), and then computed the $F$-test statistics for each of simulated spectra, thereby constructing the reference distribution for the $F$-test statistics. Comparison of the $F$-test value calculated for the data with the reference distribution for the $F$-test statistics, based on 5000 data sets simulated under the absorbed NSMAX 1200 model, gives $p < 0.0002$—which also favors the

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¹⁰ https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_xcal.html

| Model     | $N_H$ $(10^{22}$ cm$^{-2}$) | $T^e$ $(10^6$ K) | $R/D$ (km kpc$^{-1}$) | $E_0$ (keV) | FWHM (keV) | EW (keV) | $\chi^2$/dof |
|-----------|-----------------------------|------------------|------------------------|-------------|------------|----------|--------------|
| 123100    | $< 1.1$                     | 0.84 $^{+0.03}_{-0.02}$ | 5.9 $^{+0.8}_{-0.6}$   | ...         | ...        | ...      | 943/895     |
| 123190    | $< 0.3$                     | 1.34 $^{+0.01}_{-0.02}$ | 2.4 $^{+0.2}_{-0.1}$   | ...         | ...        | ...      | 977/895     |
| 1200      | $< 0.4$                     | 1.25 $^{+0.02}_{-0.01}$ | 2.4 $^{+0.2}_{-0.1}$   | ...         | ...        | ...      | 962/895     |

| Model     | $N_H$ $(10^{22}$ cm$^{-2}$) | $T^e$ $(10^6$ K) | $R/D$ (km kpc$^{-1}$) | $E_0$ (keV) | FWHM (keV) | EW (keV) | $\chi^2$/dof |
|-----------|-----------------------------|------------------|------------------------|-------------|------------|----------|--------------|
| 123100    | $2.0^{+0.9}_{-0.9}$         | 0.79 $^{+0.03}_{-0.02}$ | 7.4 $^{+1.1}_{-1.4}$   | ...         | ...        | ...      | 906/892     |
| 123190    | $< 1.3$                     | 1.29 $^{+0.02}_{-0.01}$ | 2.7 $^{+0.2}_{-0.2}$   | ...         | ...        | ...      | 907/892     |
| 1200      | $1.2^{+1.2}_{-0.9}$         | 1.16 $^{+0.05}_{-0.01}$ | 2.9 $^{+0.4}_{-0.4}$   | ...         | ...        | ...      | 902/892     |

**Note.** Temperatures $T^e$ are given as measured by a distant observer. Ratios $R/D$ are weighted averages of corresponding values for various instruments; therefore, their uncertainties account for both statistical and systematic errors. EW is equivalent width. All errors correspond to 90% HPD credible intervals, derived via MCMC.
presence of an absorption line. The same is true for models 123100 and 123190.

To set an upper limit on a non-thermal flux of Calvera, we added a power-law (PL) component to the NSMAX (1200) × GABS model and performed spectral fitting. From resulting joint posterior distribution of the spectral index $\Gamma$, and the normalization of the PL component, we got the distribution of the unabsorbed non-thermal X-ray flux in the 2–8 keV range. We then obtained its upper limit, $F_X < 4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, as the 99.7% quantile of the distribution. We did not constrain $N_H$ or $\Gamma$ during the fits. In this case, the PL component tends to fit the soft part of the spectrum, requiring unrealistically high $N_H$ and larger $\Gamma$ than expected for the pulsars. However, in the 2–8 keV range, the upper limit on the non-thermal flux is dominated by PL models with moderate $\Gamma < 4$, constrained by the hard-energy part of the X-ray spectrum. This approach provides a conservative estimate of the non-thermal limit, consistent with that reported by Zane et al. (2011), who fixed $\Gamma$ at two.

7. DISCUSSION

The deepest up-to-date optical observations of Calvera have allowed us to detect new optical objects in the arcsecond vicinity of the pulsar. The nearest object $E$ is red and locates only 0.067 from the Calvera position. However, precise astrometry showed that the offset significance is about 4.5σ; thus, $E$ can hardly be the Calvera optical counterpart. The GTC data allow us to put upper limits on the fluxes of Calvera in the $g'$ and $r'$ bands (Table 3). Assuming a flat spectrum, as it is usually observed for pulsars in the optical band, we can transform the deepest $g'$-band limit into the limit on the unabsorbed flux in the $V$ band, $F_V < 2.5 \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$. To account for the interstellar absorption, we use the total Galactic absorption in the direction of Calvera, $A_g = 0.11$ (Schlegel et al. 1998), as a conservative estimate. We also set an upper limit on the non-thermal X-ray flux of Calvera, based on archival X-ray data.

The flux upper limits constrain the Calvera optical and X-ray non-thermal luminosities, $L_V < 1.2 \times 10^{33} d_{2 \text{ kpc}}^2$ erg s$^{-1}$ and $L_{X, 2–8 \text{ keV}} < 2 \times 10^{31} d_{2 \text{ kpc}}^2$ erg s$^{-1}$, where $d_{2 \text{ kpc}}$ is distance in units of 2 kpc. In Figure 4, we compare them with corresponding luminosities of other pulsars on $L – \dot{E}$ diagrams. The X-ray data are adapted from Kargaltsev & Pavlov (2008) 11, and the optical data are taken from Danilenko et al. (2013). We also add the data for PSR J1741−2054. The X-ray luminosity is taken from Karpova et al. (2014), and the optical data are from Mignani et al. (2016). For both bands, an uncertainty factor of two, on the distance, is taken into account (Karpova et al. 2014; Mignani et al. 2016). Dashed lines correspond to different optical and X-ray efficiencies $\eta_V \equiv L_V/\dot{E}$ and $\eta_X \equiv L_X/\dot{E}$. The least-efficient pulsar is Vela—other pulsars have optical efficiencies in the range of $10^{-5}–10^{-4}$, and X-ray efficiencies in the range of $10^{-5}–10^{-1}$. It can be seen that Calvera is not an outlier on these diagrams, if we assume a distance of 2 kpc or more. It is possible that Calvera is as inefficient in the optical and X-rays as the Vela pulsar.

According to results of X-ray spectral fittings (Table 4), such a distance implies that an observed thermal emission originates from a significant portion of a NS surface (assuming standard NS radii of $\sim 10–15$ km). The basic argument against this possibility is a relatively large pulsed fraction of the Calvera X-ray emission (Halpern et al. 2013). It was shown by Page (1995) that an NS with a smooth surface temperature map emitting as a blackbody can show no more than 10% of the pulsed fraction, due to gravitational bending effects. However, for magnetic atmospheres, the situation is different because the specific flux emerging from the surface has the intrinsic anisotropy. This anisotropy results in a “pencil” or “fan” emission beam shape (Zavlin et al. 1996) that is a consequence of the magnetic-field-induced radiative transfer anisotropy in atmospheric layers. Therefore, an NS covered with magnetized atmosphere can show pulsations even if its surface effective temperature is uniform (Shibanov et al. 1995). Interestingly, the calculations given in Shibanov et al. (1995) result in a similar dependence of the pulsed fraction on photon energy, as observed for Calvera. Namely, Halpern et al. (2013) found that the pulsed fraction is $\approx 10\%$ at energies below 0.5 keV, and

11 Their luminosities in 0.5–8.0 keV band were transformed to luminosities in 2.0–8.0 keV band.
≈30% above 0.5 keV, which is in accord with the pulsed fraction calculated for the NS with dipole magnetic field $B = 10^{12}$ G, covered by a hydrogen atmosphere (Shibanov et al. 1995).

We found that the X-ray spectrum of Calvera is indeed well-fitted by the hydrogen atmosphere model NSMAX, with addition of the spectral absorption feature at about 0.7 keV (Table 4). A similar conclusion was reached by Zane et al. (2011), who used the NSA model for the thermal continuum. Atmospheric model 1200, with uniform distribution of temperature over the NS surface and radial magnetic field, results in the distance $D \sim 5$ kpc, if we assume that X-rays are coming from the bulk of the NS surface. Although this model may be suitable for the phase-averaged spectrum, it cannot—for of course—explain pulsations. In order to quantify the pulse shape, and to get more relevant model for the phase-averaged spectrum, we need to account for (or fit) the pulsar geometry. In other words, we need to account for the relative position of three vectors—the magnetic axis, rotational axis, and line of sight. For instance, the results of Shibanov et al. (1995) are for the orthogonal rotator, when the rotational axis is perpendicular to both the magnetic axis and the line of sight.

The quantitative fit of the pulsar geometry to the observed phase-dependent spectrum is a good project for the future, but outside the scope of the present paper. Attempts at performing such fits, taking into account the atmospheric effects in approximate ways, are given in, e.g., Shabaltas & Lai (2012) and Bogdanov (2014). A possible impact of the more realistic consideration is illustrated by the fit results with NSMAX models 123100 and 123190. These models are calculated assuming the dipole surface magnetic field, with $B = 10^{12}$ G at the magnetic equator and corresponding non-uniform temperature distribution (Ho et al. 2008). The results following from these models can be considered as limiting cases of the real pulsar viewing geometry, because model 123100 assumes that the line of sight coincides with the magnetic moment direction, whereas, in the case of model 123190, these vectors are orthogonal. The former case corresponds to the situation when hotter polar regions of the star are seen most of the time, whereas in the latter case, one observes colder equatorial regions. As follows from Table 4, Calvera can be at $D \approx 1.5-5$ kpc, if covered with magnetized hydrogen atmosphere. The large distance to Calvera implies that $N_H$ must be compatible with the total Galactic absorption column density in this direction, $N_H = 2.7 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). Values for $N_H$, derived from the 1200 and 123100 fits with the absorption line, are consistent with the total Galactic column density. The spectral fit for the 12390 model formally gives the limit which is two times lower than the total column density. However, we checked that fixing $N_H$ at $2.7 \times 10^{20}$ cm$^{-2}$ does not substantially affect the fit quality and parameter values.

Figure 3. 1D and 2D marginalized posterior distributions for model NSMAX(1200)×GABS. Gray-filled regions correspond to 90% HPD credible intervals. Contours are for 40%, 68%, 90%, and 99% levels.
If the distance to Calvera is indeed 1.5 kpc or more, the pulsar is high above the Galactic disc—either it was ejected from there at a high speed, or its progenitor was a runaway star. The relatively small proper motion measured by Halpern & Gotthelf (2015) invalidates the former possibility. It is interesting that a similar situation occurs for the radio-pulsar J1740+1000, which resembles Calvera (Halpern et al. 2013). That pulsar is also undetected in γ-rays, with an upper limit on γ-ray luminosity an order of magnitude below those of pulsars of similar $E$. The X-ray non-thermal luminosity of J1740+1000 is marked by the red bar in Figure 4. It can be seen that J1740+1000 is an inefficient X-ray pulsar. The J1740+1000 distance of 1.4 kpc, based on dispersion measure (DM) (McLaughlin et al. 2002), implies that it is also high above the Galactic disc; however, no significant proper motion was found (Halpern et al. 2013). Thus, a runaway-star progenitor is the only possibility for PSR J1740+1000 (if the DM distance is correct). Consequently, the runaway-star interpretation for Calvera’s progenitor seems plausible as well.

The above consideration shows that a relatively large distance to Calvera could be in accord with its thermal spectral properties, as well as optical and X-ray non-thermal efficiencies. In this case, Calvera could be an ordinary RPP. The most puzzling thing, however, is non-detection of the γ-ray flux with an upper limit on the γ-ray luminosity of $L_\gamma < 3.3 \times 10^{32} d_\text{kpc}^2 \text{erg s}^{-1}$ (Halpern et al. 2013). Even if Calvera is at a distance of 5 kpc, it is at the lower edge of corresponding luminosities of other pulsars with similar $E$; see Figure 5 from Halpern et al. (2013).

Finally, in our Figure 5, we present a current update to the multwavelength appearance of Calvera. The upper limits on the optical and non-thermal X-ray unabsorbed flux densities, shown with arrows, are compared with the best-fit atmospheric models (Table 4) extrapolated to lower energies. The thermal component is clearly unreachable in the optical (Zane et al. 2011), but if Calvera is an RPP, the possible non-thermal component could have been seen. For the middle-aged RPPs detected in the optical and X-rays, the peak of the NS surface thermal emission usually exceeds the non-thermal background of the pulsar magnetosphere origin; however, the magnitude of the excess could be different. For instance, for PSR J1741−2054, whose optical counterpart candidate was recently detected (Mignani et al. 2016), this excess is about one order of magnitude. The same situation probably occurs for PSR J1357−6429 (Zyuzin et al. 2016, Figure 3). In contrast, for well-studied Geminga, B0656+14, and PSR B1055−52, the thermal peak heights are 2–3 mag higher than the non-thermal level (Kargaltsev et al. 2005; Mignani et al. 2010; Durant et al. 2011). The relative position of the Calvera optical upper limit, with respect to the thermal peak, is intermediate between these possibilities—encouraging deeper studies.

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12 We do not continue atmospheric models in the optical, because NSMAX calculations are not available there.
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**Facilities:** GTC, CXO, XMM-Newton, Gemini-N.

**APPENDIX**

**NONLINEARITY OF THE HRC PLATE**

Usually, the HRC plate is assumed to be linear, at least within several arcminutes of the telescope optical axis (e.g., Beckerman et al. 2004; Halpern & Gotthelf 2015). Because accurate astrometry uncertainty estimation is crucial to our goals, we directly examined the possible nonlinearity of the HRC-I image. That is, we selected archival HRC-I observation of σ Orionis (ObsId 2569, PI Wolk) containing sufficient amounts of the point-like X-ray sources that have well-defined optical counterparts in the 2MASS catalog. Using the IRAF/daophot/ccmap task, we then constructed two astrometric solutions; one assuming pure linear transformation, and the general one. For reference, we used 22 sources located within 5′5 from the optical axis. The difference between the WCS coordinates given by these solutions was found to be less than 0′05, inside the central 2′ detector area. We consider this difference to be a systematic error that should be included in the overall HRC-I astrometric uncertainty budget.

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