Discovery of 59 ms Pulsations from 1RXS J141256.0+792204 (Calvera)

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\textbf{ABSTRACT}

We report on the results of a multi-wavelength study of the compact object candidate 1RXS J141256.0+792204 (Calvera). Calvera was observed in the X-rays with {	extit{XMM-Newton}}/EPIC twice for a total exposure time of $\sim 50$ ks. The source spectrum is thermal and well reproduced by a two component model composed of either two (absorbed) hydrogen atmosphere models, or two blackbodies with temperatures $kT_1 \sim 55/150$ eV, $kT_2 \sim 80/250$ eV, respectively (as measured at infinity). Evidence was found for an absorption feature at $\sim 0.65$ keV while no power-law high-energy tail is statistically required. Using pn and MOS data we discovered pulsations in the X-ray emission at a period $P = 59.2$ ms. The detection is highly significant ($\gtrsim 11\sigma$), and unambiguously confirms the neutron star nature of Calvera. The pulse profile is nearly sinusoidal, with a pulsed fraction of $\sim 18\%$. We looked for the timing signature of Calvera in the \textit{Fermi} Large Area Telescope (LAT) database and found a significant ($\sim 5\sigma$) pulsed signal at a period coincident with the X-ray value. The gamma-ray timing analysis yielded a tight upper limit on the period derivative, $\dot{P} < 5 \times 10^{-18} \, \text{s}^{-1}$ ($\dot{E}_{\text{rot}} < 10^{33}$ erg s$^{-1}$, $B < 5 \times 10^{10}$ G for magneto-dipolar spin-down). Radio searches at 1.36 GHz with the 100-m Effelsberg radio telescope yielded negative results, with a deep upper limit on the pulsed flux of 0.05 mJy. Diffuse, soft ($< 1$ keV) X-ray emission about 13' west of the Calvera position is present both in our pointed observations and in archive \textit{ROSAT} all-sky survey images, but is unlikely associated with the X-ray pulsar. Its spectrum is compatible with an old supernova remnant (SNR); no evidence for diffuse emission in the radio and optical bands was found. The most likely interpretations are that Calvera is either a central compact object escaped from a SNR or a mildly recycled pulsar; in both cases the source would be the first ever member of the class detected at gamma-ray energies.

\textbf{Key words:} Gamma-ray: stars – pulsars: general – pulsars: individual: 1RXS J141256.0+792204 (Calvera) – stars: neutron – X-ray: stars

1 INTRODUCTION

Isolated neutron stars (NSs) have been for a long time associated with radio pulsars. It was only during the last two decades, thanks to multi-wavelength observations from both space and ground-based instruments, that our picture of the Galactic NS population changed. These observations unveiled the existence of different types of isolated NSs which are radio quiet or have radio properties quite at variance with those of ordinary pulsars. Examples are the soft gamma repeaters and the anomalous X-ray pulsars (the likely magnetars; e.g. \cite{WoodsThompson2006, Mereghetti2008}), the central compact objects (CCOs; e.g.
In this respect, it appears very promising that two new, apparently radio quiet X-ray sources have been recently proposed as isolated NS candidates. These are 1RXS J141256.0+792204 (dubbed Calvera; Hessels et al. 2007; Rutledge, Fox & Shevchuk 2008; Shevchuk, Fox & Rutledge 2009), which was found in the ROSAT Bright Source Catalogue (RBSC, Voges et al. 1999), and, at fainter flux levels, 2XMM J104608.7-594306, discovered with XMM–Newton (Pires et al. 2009).

Calvera, in particular, is a puzzling source and its interpretation represented a conundrum (see § 2). At variance with most known radio quiet isolated NSs, the source is at high Galactic latitude, and it exhibits a quite hot, thermal spectrum with little absorption. Calvera was first selected in the RBSC and identified as a possible isolated NS candidate on the basis of its large X-ray-to-optical flux ratio. The source was then observed with the Swift-XRT and with Chandra (see § 2 for details of the past observations, and references therein). In particular, the first, short (~2 ks) Chandra pointing (obs. ID: 8508) provided a refined X-ray position and follow-up Gemini observations confirmed the lack of optical counterparts down to $g \sim 26.3$, implying $F_X/F_{opt} > 9000$ (Rutledge, Fox & Shevchuk 2008). However, despite the improved spectral information, these data were insufficient to discriminate among the different interpretations for its nature.

Clearly, better spectral and timing information is crucial to unambiguously classify the source. Here, we present a multi-wavelength study of Calvera, based on two new XMM–Newton observations, on the analysis of publicly available Fermi–LAT data, and on a new radio observation taken at the 100-m Effelsberg telescope. We also used Chandra and ROSAT archival data. The paper is organised as follows. We first summarise the results from the past observations and the proposed scenarios in § 2. Spectral and timing results from the XMM–Newton and Fermi–LAT observations are presented in § 3, while the radio observations are summarised in § 4. A search for potential sources of diffuse X-ray or radio emission in the proximity of Calvera is presented in § 5. Discussion and conclusions follow in § 6.
is deep enough to rule out both a white or a red dwarf companion. If this is the case, Calvera would thus be one of the few solitary field millisecond pulsars discovered so far (about 18 known isolated millisecond pulsars in the Galactic plane, comprising roughly 30% of the population).

In order to shed further light on these possibilities, Rutledge, Fox & Shevchuk (2008) re-observed the source with Chandra for 30 ks on 2008 April 8 (obs. ID: 9141). This longer observation allowed them to exclude (absorbed) single-component spectral models, as a BB, a PL or a pure hydrogen atmospheric model (NSA; Zavlin, Pavlov & Shibanov 1996), since they all gave unacceptable large values of $\chi^2$ and, in some cases, a value of the column density larger than the Galactic one in the source direction ($N_{\text{col}} = 2.65 \times 10^{20}$ cm$^{-2}$; Kalberla et al. 2003). Instead, these authors proposed as best fit a NSA model (with effective temperature of $\approx 110 - 120$ eV) combined with a spectral feature, either an edge or more likely an emission line, at $\sim 0.5 - 0.6$ keV. The source did not show signs of variability neither on short nor long ($> 1$ year) timescales, and pulsations have not been detected down to a 3σ limit in pulsed fraction (defined as the semi-amplitude of the sinusoidal modulation divided by the mean source count rate) in the period range between 0.9 s and 10 s. The absence of a non-thermal spectral component and the relatively low limit on the pulsed fraction for periods of a few seconds made a magnetar interpretation unlikely, but the other possibilities still remained open. Therefore, despite the better spectrum, the Chandra data (obs. ID: 9141) did not provide sufficient clues to solve the conundrum proposed by Rutledge, Fox & Shevchuk (2008) about the nature of the source.

### 3 X-RAY AND GAMMA-RAY OBSERVATIONS

#### 3.1 Source position and association

We started our analysis by first accurately re-assessing the source position determination. This is particularly important because a large positional error precludes firmly ruling out the association with the close-by ($\sim 0.9''$) $g \sim 24.8$ Star A (Rutledge, Fox & Shevchuk 2008). Based on a Chandra/HRC-I observation (obs. ID: 8508), Rutledge, Fox & Shevchuk (2008) gave: $\alpha = 14^{1}12^{m}55^{s}385, \delta = +79^{0}22\arcmin0.10$, with a 90% uncertainty of 0.057, after applying a bore sight correction of $\Delta \alpha \approx -0.04 \pm 0.22$ and $\Delta \delta = +0.155 \pm 0.02$ to the Chandra astrometry. To this aim, they used as a reference the optical coordinates of a second source, CXOU J141259.43+791958, detected in the HRC-I field, derived from those of its putative counterpart identified in their Gemini images, calibrated with the USNO-B1.0 catalogue (Monet et al. 2003). However, this procedure comes with some caveats.

To verify the value of the Rutledge, Fox & Shevchuk (2008) coordinates, we retrieved the HRC-I data set (obs. ID: 8508) from the public Chandra archive. First of all, we found that their reference X-ray source has a count rate of $\approx 0.005$ cts/s ($\approx 2.5\sigma$ detection significance), which lowers the accuracy of the bore sight correction. Furthermore, using only one reference source can introduce systematics due to a proper motion of its putative optical counterpart. Since the default reference epoch for the USNO-B1.0 coordinates is 2000.0 while the epoch of the Chandra/HRC-I observation (obs. ID: 8508) is 2007.13, the effect on the bore sight correction can be significant. We identified the putative counterpart of the reference X-ray source with the USNO-B1.0 star 1693-0051235 ($B = 20.51; R = 19.4$). According to the catalogue, this star has a proper motion $\mu_{\alpha} = -6 \pm 4$ mas yr$^{-1}$ and $\mu_{\delta} = 6 \pm 1$ mas yr$^{-1}$, with $\pm 4$ mas yr$^{-1}$ being a more realistic uncertainty for the latter value (see e.g. Gould 2004). This would imply an offset of $\Delta \alpha \sim 42 \pm 28$ mas and $\Delta \delta = -42 \pm 28$ mas in the bore sight correction, apparently not accounted for in Rutledge, Fox & Shevchuk (2008). While this offset would be negligible within the error budget of the Chandra and of the USNO-B1.0-based astrometry calibration of the Gemini images (Rutledge, Fox & Shevchuk 2008), we can not rule out that the star has a larger proper motion. We queried other astrometric catalogues to verify the USNO-B1.0 proper motion. Unfortunately, the star is too faint to be in the UCAC-3 catalogue (Zacharias et al. 2010) while it appears in the PPMXL (Roeser, Demleitner & Schilbach 2010) which gives $\mu_{\alpha} = -7.1 \pm 5.6$ mas yr$^{-1}$ and $\mu_{\delta} = 6.1 \pm 5.6$ mas yr$^{-1}$, consistent with the USNO-B1.0 value although not statistically significant yet. From this value, we set a 3σ upper limit on the star proper motion of $\mu_{\alpha} = 24$ mas yr$^{-1}$ and $\mu_{\delta} = 23$ mas yr$^{-1}$. Thus, we estimate an additional uncertainty of $\sim 0.17$ (per coordinate) to the one-star bore sight correction of Rutledge, Fox & Shevchuk (2008), rising its total uncertainty to $0.28$ (per coordinate).

We independently measured the coordinates of Calvera in the HRC-I dataset, after it was corrected for the reported offset in the absolute Chandra astrometry. Our best fit coordinates are then $\alpha = 14^{1}12^{m}55^{s}58.85, \delta = +79^{0}22\arcmin0.7$, with a 90% confidence error of 0.6. Given the re-assessed uncertainty on the one-star bore sight correction (see above), we decided not to apply it to the measured coordinates of Calvera.

A second Chandra observation of Calvera was performed with the ACIS-S detector (Shevchuk, Fox & Rutledge 2009, obs. ID: 9141). We retrieved the ACIS-S dataset from the public Chandra archive and we measured the position of Calvera as $\alpha = 14^{1}12^{m}55^{s}54.6, \delta = +79^{0}22\arcmin0.37$, with a 90% confidence error of 0.6. This position is consistent with that measured by us using the HRC-I data set and, obviously, virtually identical to that obtained by Shevchuk, Fox & Rutledge (2009) from the uncorrected Chandra astrometry. We noticed that Shevchuk, Fox & Rutledge (2009) applied the bore sight correction of the ACIS-S image, using the position of the optical counterparts to two field sources, CXOU

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1 As the authors noted, this large correction was probably due to a systematic 0.4 offset in the absolute Chandra astrometry affecting data taken after 2006 December 1.
J141220.78+792251.6 and CXOU J141246.23+792222.3. They then obtained $\alpha = 14^{h}12^{m}55.76, \delta = +79^{\circ}22^{\prime}03^{\prime\prime}$ with a quoted 90% uncertainty of 0$^{\prime}$31 and 0$^{\prime}$3 in right ascension and declination, respectively. However, we could not detect these two sources in the ACIS-S (above a detection threshold of 3$\sigma$, see Fig. 1 left panel). We confirm, instead, the marginal detection of a faint source, CXOU J141252.41+792152.60, in the ACIS-S data located ~20$^{\prime}$ south west of Calvera, which was not detected in the HRC-I data (obs. ID: 8508), while the HRC-I source CXOU $\sim$ CXOU J141252.41+792152.60 was in timing mode, covering the target and the surrounding field (central CCD + 5 outer CCDs), while MOS2 was in timing mode (imaging for outer 6 CCDs). Green circles correspond to the nominal Chandra position in the present analysis. Because of the non-detection of the two sources claimed by Shevchuk, Fox & Rutledge (2009) in the ACIS-S data, we used the nominal Chandra position in the present analysis.

Finally, for the sake of completeness we checked our XMM–Newton observations. XMM–Newton observed Calvera twice in 2009, on August 31 and October 10, for a total exposure of about 47 ks. The observations were performed with the EPIC pn (Strüder et al. 2001) and MOS (Turner et al. 2001) cameras in different CCD read out modes (see Table 1). The net exposure from the first observation (obs. ID: 0601180101) was short: less sources were detected and no bore sight correction was performed. From the second observation (obs. ID: 0601180201), we obtained $\alpha = 14^{h}12^{m}55.48, \delta = +79^{\circ}22^{\prime}03^{\prime\prime}$, as computed by the EPIC pipeline (1$\sigma$ statistical error of 0$^{\prime}$21) which computes the bore sight correction from the positions of X-ray sources in the field matched against those of optical sources in, e.g. the USNO-B1.0, NED, and NOMAD catalogues. In this case, the pipeline finds 35 X-ray sources with optical matches. However, we visually inspected the X-ray source position on the DSS-2 images and we found possible matches with 14 optical sources, of which only 4 are listed both in the GSC-2 (Lasker et al. 2008) and in the 2MASS (Skrutskie et al. 2006) catalogues. By matching the pixel-to-sky coordinates of the X-ray sources and their associated 2MASS/GSC-2 counterparts we derived an astrometric solution with an rms of 0$^{\prime}$88 and we determined $\alpha = 14^{h}12^{m}55.68, \delta = +79^{\circ}22^{\prime}04^{\prime\prime}$.2 for Calvera, formally more consistent with the coordinates obtained from the Chandra data sets.

We notice that the two sources used by Shevchuk, Fox & Rutledge (2009) for the Chandra bore sight are also not detected by XMM–Newton (see Fig. 1 right panel). From the sensitivity map of observation possible matches with 14 optical sources, of which only 4 are listed both in the GSC-2 (Lasker et al. 2008) and in the 2MASS (Skrutskie et al. 2006) catalogues. By matching the pixel-to-sky coordinates of the X-ray sources and their associated 2MASS/GSC-2 counterparts we derived an astrometric solution with an rms of 0$^{\prime}$88 and we determined $\alpha = 14^{h}12^{m}55.68, \delta = +79^{\circ}22^{\prime}04^{\prime\prime}$.2 for Calvera, formally more consistent with the coordinates obtained from the Chandra data sets. We notice that the two sources used by Shevchuk, Fox & Rutledge (2009) for the Chandra bore sight are also not detected by XMM–Newton (see Fig. 1 right panel). From the sensitivity map of observation
601180201 (pipeline), the 3σ upper limit for the two sources is 0.005 cts/s (in the EPIC total band 0.2-12 keV), a factor of 30 lower than the count rate of Calvera. This converts to a flux of $\approx 3 \times 10^{-14}$ erg cm$^{-2}$s$^{-1}$, with sizeable uncertainties depending on the assumed spectral model.

In conclusion, through our astrometry analysis we conclude that the most reliable coordinates of Calvera are those derived from the Chandra astrometry ($\alpha = 14^h 12^m 55.84^s$, $\delta = +79^\circ 22' 03'' 7$, with a 90% confidence error of 0'.6) i.e. without applying uncertain bore sight corrections, and they indeed confirm that Calvera is not associated with star A from Rutledge, Fox & Shevchuk (2005). Moreover, we note that the uncertainty on the Calvera coordinates is small enough not to hamper a sensitive search for coherent signals in our timing analyses (see § 3.2).

3.2 XMM-Newton data analysis

For both, spectral and timing analysis we used the latest XMM-Newton Science Analysis Software (SAS), version 10.0.1. We checked that the pn event files produced by "epchain" were clean of unrecognised time jumps before we applied an event time randomisation.

We extracted source spectra for Calvera from the imaging mode data of pn and MOS1 using a circular region around the target position with 15'' radius and background spectra from a nearby source-free region of same size. Based on its low number of counts (see Fig. 1 and caption), CXOU J141252.41+792152.60 is not expected to contaminate Calvera’s data. Since the spectral response in MOS timing mode is currently not well calibrated, we did not use the MOS2 timing data for spectral analysis. For spectra we selected single pixel events (corresponding to PATTERN=0) for pn and all valid events for MOS (PATTERN=0-12), excluding bad CCD pixels and columns (FLAG=0). We used XSPEC version 12.5.0 for spectral modelling.

The same pn and MOS event lists considered for the spectral analysis were also used as input for the timing analysis (with different background screening criteria, see Table 1). In addition, in order to obtain better temporal resolution, we used also the MOS2 data. MOS2 was operated in timing mode; in this mode data from the central CCD are collapsed into a one-dimensional row to achieve a ~1.75 ms time resolution. Therefore, instead of a circular extraction region, we used a rectangular box of 20 pixel width. The local background was measured in a region of the images far from the extracted source itself and taking care that no other source falls within the extraction regions by chance (as we already noticed, the Chandra source CXOU J141252.41+792152.60 is unresolved from Calvera, see § 3.1). The arrival times of the photons were corrected to the barycenter of the Solar System using the JPL DE405 Solar System ephemeris (Standish 2004) and the SAS task "BARYCENT".

3.3 XMM-Newton spectral analysis: pulse averaged spectra

Spectra were accumulated from the pn and MOS1 event lists after removing those time intervals affected by solar proton flares resulting in an effective exposure time of ~14 ks (pn) and ~19.7 ks (MOS1; first observation, obs. ID: 0601180101), 19.5 ks (pn) and 27.5 ks (MOS1; second observation, obs. ID: 0601180201).

We started the analysis considering an absorbed double BB model and fitting the two pn and the two MOS1 spectra simultaneously, allowing only a renormalisation factor to account for cross-calibration uncertainties between the detectors and possible time-variability of the source. To account for interstellar absorption, here and in the following we adopted the elemental abundances of Wilms, Allen & McCray (2000) model "phabs" in XSPEC. We note here that the used metal abundances influence the derived equivalent hydrogen column density and can introduce systematic uncertainties when comparing its value with HI-derived column densities. We did not find flux variations greater than 3% between the two observations, which is consistent, considering the statistical uncertainties, with a steady source flux. We then performed an independent fit of the spectra from the first and the second observation (still joining pn and MOS data within each epoch). The resulting best-fit parameters, from the two epochs, were consistent within their statistical errors.

Since the source showed neither significant flux variations nor spectral changes between the two XMM-Newton observations, in the rest of the analysis we fitted all pn and MOS data together in order to obtain the best signal to noise ratio. We tested several single, double and triple component spectral models, based on different combinations of BBs, PLs, NS atmosphere models (NSA) and absorption edges or Gaussian lines. In the NSA model, we used $R_{\text{star}} = 12$ km and $M_{\text{star}} = 1.4M_{\odot}$ as input parameters for the NS radius and mass. The results are summarised in Table 2 where we report only the fluxes inferred from the pn data of observation 0601180101. As mentioned above, we do not see significant flux variations between the two observations: computing an average pn flux for the two observations, weighted with the exposures, gives a value 0.98 times smaller than that reported in Table 2. Also, the fluxes obtained from the MOS1 spectra are consistent with those listed in the table. We warn the reader that the parameters reported in Table 2 have a different physical meaning inasmuch the best fit temperatures obtained by the BB fit are measured at infinity, while those from the NSA model are measured at the neutron star surface. The two quantities are related by $T_{\infty} = T/(1+z)$ where $1+z \equiv 1/\sqrt{1-2.952M_{\text{star}}/R_{\text{star}}}$ is the gravitational redshift factor.

In agreement with Shevchuk, Fox & Rutledge (2000), we find that single component models do not provide a good representation of the Calvera spectrum. However, the advantage of the EPIC spectra is the higher efficiency of the instruments below 500 eV, where the Chandra spectrum has very few counts. Fitting the XMM-Newton data with one component models leaves a low energy excess, that can be accounted for by a second emission component. Two-component models including a PL (as in the combinations PL+BB, PL+NSA) demonstrate a problem: the additional PL is always very steep and represents the soft part of the spectrum (requiring a high interstellar absorption), instead of a hard tail as usually seen from isolated NSs with a non-thermal component (De Luca et al. 2003). Instead, we found that the best two-component fits are composed of either, two thermal components (BB+BB,
Table 2. Summary of spectral fits.

| Model           | $\chi^2 / \text{d.o.f.}$ | $N_H \, 10^{20}$ cm$^{-2}$ | $\Gamma$ | $kT$ (a) | $E_{\text{edge}} / E_{\text{line}}$ | $\tau / \sigma$ | $F_{\text{bol}}^{(b)} \, 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ | $F_{\text{bol}}^{(c)} \, 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ | Comment       |
|-----------------|----------------------------|------------------------------|-----------|----------|-----------------------------------|-----------------|------------------------------------------------|------------------------------------------------|--------------|
| PL$^{(d)}$      | 1.843/326                  | 11.9                         | 3.4       |          |                                   |                 | 9.12                                               |                                    | $N_H > N_{gal}^{(e)}$ |
| PL + BB         | 1.055/324                  | 8.9±1.0                      | 3.8±0.3   | 227±8    |                                   |                 | 8.58                                               | 0.51                                             | $N_H > N_{gal}^{(e)}$ |
| PL + NSA        | 1.051/324                  | 9.1±0.8                      | 4.3±0.5   | 111±7    |                                   |                 | 8.49                                               | 1.28                                             | $N_H > N_{gal}^{(e)}$ |
| BB$^{(d)}$      | 2.258/326                  | 0.0                          |          |          |                                   |                 | 8.12                                               | 0.84                                             | $N_H > N_{gal}^{(e)}$ |
| 2BB             | 1.053/324                  | 4.6±1.0                      | 93±8/242±9|          |                                   |                 | 8.40                                               | 0.79/0.67                                         | $N_H > N_{gal}^{(e)}$ |
| 2BB             | 1.096/325                  | 2.7(f)                       | 110±6/253±10|          |                                   |                 | 8.48                                               | 0.58/0.59                                         | $N_H > N_{gal}^{(e)}$ |
| BB × edge       | 1.486/324                  | 0.5±0.3                      | 201±3     | 0.66±12/17 | 0.67±0.08                         | 8.30            | 1.02                                               |                                                  |               |
| BB – gauss      | 1.631/324                  | 0.5±0.3                      | 196±3     | 0.76±0.02 | 0.1(f)                            | 8.23            | 0.97                                               | EW = −83 eV                                     |               |
| 2BB × edge      | 1.051/323                  | 2.7(f)                       | 123±11/254±15| 0.63±0.03 | 0.26±0.11                         | 8.47            | 0.61/0.58                                         |                                                  |               |
| 2BB – gauss     | 1.015/322                  | 2.7(f)                       | 140±14/283±30| 0.66±0.05 | 0.13±0.05                         | 8.51            | 0.82/0.41                                         | EW = −79 eV                                     |               |
| NSA             | 1.347/326                  | 1.8±0.4                      | 98±3      |          |                                   | 8.37            | 1.65                                               |                                                  |               |
| 2NSA            | 1.042/324                  | 6.7±1.3                      | 27±6/118±7 |          |                                   | 8.47            | 1.38/3.00                                         | $N_H > N_{gal}^{(e)}$                          |               |
| 2NSA            | 1.156/325                  | 2.7(f)                       | 67±12/150±12 |          |                                   | 8.56            | 0.76/1.16                                         |                                                  |               |
| NSA × edge      | 1.079/324                  | 2.6±0.5                      | 97±3      | 0.65±0.02 | 0.40±0.08                         | 8.43            | 1.92                                               |                                                  |               |
| NSA + gauss     | 1.304/325                  | 1.5±0.4                      | 101±4     | 0.53(f) | 0.0(f)                            | 8.40            | 1.59                                               | EW = 12 eV                                      |               |
| 2NSA × edge     | 1.053/323                  | 2.7(f)                       | 82±12/17/154±200 | 0.64±0.03 | 0.31±0.09                         | 8.53            | 0.46/1.45                                         |                                                  |               |

(a) BB and NSA temperatures are evaluated at infinity and at the NS surface, respectively. It is $T_{\infty} = T/(1+z)$, see text for details.
(b) Observed flux in the 0.2–10 keV band derived from the EPIC pn spectrum of the first observation. (c) Bolometric flux for the thermal components (NSA and BB) derived from the EPIC pn spectrum of observation 0601180101. (d) No error estimate due to bad fit. (e) $N_{gal} = 2.65 \times 10^{20}$ cm$^{-2}$, [Kalberla et al. 2003]. (f) Parameter fixed in the fit.

Figure 2. Left panel: EPIC pn and MOS1 spectra fitted with a double blackbody model. Right panel: EPIC pn and MOS1 spectra modelled with a double NSA model. Both figures show best-fitting models in which the value of $N_H$ has been left free. See Table 2 and text for details.

NSA+NSA), or an NSA+edge model. One difference is that, while the NSA+edge fit gives a value of $N_H$ consistent with the Galactic one (as in the case of the Chandra data, Shevchuk, Fox & Rutledge 2009), the fits with two thermal components give a larger value, which may suggest the presence of a local absorption component. However, fixing the $N_H$ at the Galactic value does not deteriorate the fits considerably (see, again, Table 2). Data and best-fitting models based on two thermal components (BB+BB and NSA+NSA) with free $N_H$ are shown in Fig. 2. Unfortunately, based on present spectral data only, it is not possible to discriminate between a picture in which the spectrum originates from two zones of the NS surface (with temperatures at infinity of $\sim$ 80 and 250 eV if the emission is modelled with black-bodies, or $\sim$ 55 and 150 eV if NSA models are used), and one in which the star surface is at uniform temperature (of $T_{\infty} \sim$ 80 eV, NSA) with an absorption edge at $\sim$0.65 keV present in the spectrum (for a discussion about the possible discrimination based on other arguments, see § 6.1).

We notice that, in the BB+BB and NSA+NSA models, the contributions of the two thermal components cross near $\sim$0.65 keV, which is probably the reason why the spectral fit can be accomodated by introducing a feature around this energy. This is at odds with Shevchuk, Fox & Rutledge (2009), who proposed as a best-fitting model a NSA plus emission line: including a Gaussian emission line in the NSA
3.4 XMM-Newton timing analysis

Given the rather different observing modes and sampling time among the three instruments (Δt of ~5.67 ms, 1.75 ms and 2.6 s for pn, MOS2 and MOS1, respectively) we first used all the event lists extracted from the three instruments during the two observations together, and assumed the largest (MOS1) sampling time in order to look for signals with periods larger than 5.2 s. Moreover, in order to maximise the sensitivity of the coherent pulsation search we minimise to two (one for each observation) the number of averaged power spectra. Significant power spectrum peaks were searched for by using the algorithm described in Israel & Stella (1996). No significant peak (above a 3σ confidence threshold on 2,097.152 frequency trials) has been found. The corresponding 3σ upper limit on the pulsed fraction (defined as the semi-amplitude of modulation divided by the mean source count rate) is about 10% in the 5.2-10^9 s range (consistent, although tighter, with the constraints set by Shevchuk, Fox & Rutledge 2009).

The signal search was then carried out by using the pn and MOS2 event lists only and with a time resolution of 5.67 ms in order to sample periods as short as ~12 ms. A highly significant peak (~11.5σ; see Fig. 3) was found at a frequency of 16.89242(2) Hz, corresponding to a period of 59.19816(7) ms (uncertainties refer to the intrinsic Fourier resolution of the power spectrum in Figure 3). Such a short period of 59.19821(1) ms or ν=16.892404(5) Hz (90% confidence, 55094 MJD). Unfortunately the inferred accuracy is not enough to keep the phase coherency between the two observations which are separated by about 40 days (the inferred period uncertainty of the first XMM-Newton observation, can be obtained by fitting the phases of the modulation over different time intervals. However, we noticed that the simultaneous MOS2 and pn light curves folded to the above period show a phase shift of about 0.10 and 0.15 (for the first and second observation, respectively), making any results inferred from the phase fitting analysis unreliable. The presence of both phase shift and pulse distortion between MOS and pn was also detected in other relatively fast pulsars, such as PSR B1706-44 (with a pulse period of 102 ms; McGowan et al. 2004). In order to further check for the presence of the observed phase shift we also analysed the data from another pulsar, namely PSR B1509-58 (pulse period of ~150 ms), observed by XMM–Newton in September 2000 with the pn and MOS2 in the same observational modes also set for our observations. The pn and MOS2 folded light curves of PSR B1509-58 are reported in Figure 3. The phase shift is statistically significant and equal to 0.050±0.001, corresponding to 7.5±0.2 ms. Therefore, in the following we decide to use only the pn data given that no calibration to assess the absolute timing accuracy of the MOS exists (see the latest XMM–Newton EPIC technical report), and because of the pn larger statistics.

In order to obtain a refined value of the period we divided the first pn observation (obs. ID: 0601180101) in four time intervals of duration ~5000 s and inferred the phase of the modulation in each interval (see Dall’Osso et al. 2004 for more details). The scatter of the phase residuals was consistent with a strictly periodic modulation at the best period of P=59.19821(1) ms or ν=16.892404(5) Hz (90% confidence, 55094 MJD). Unfortunately the inferred accuracy is not enough to keep the phase coherency between the two observations which are separated by about 40 days (the inferred period uncertainty of the first XMM-Newton
Another period measurement and therefore a measure of the $P$ or a more constraining upper limit on it. No coherent signal was found, and the corresponding $3\sigma$ upper limit on the pulsed fraction is larger than 100%.

### 3.5 Gamma-ray data analysis and results

Gamma-ray observations could represent an important step to unveil the nature of Calvera. In particular, the detection of pulsed emission at gamma-ray energies can in principle be useful to constrain the period derivative (and then the rotational energy loss rate) thanks to the large data spans typically provided by the current generation of gamma-ray telescopes with time tagging accuracy as low as a few $\mu$s.

Hence, we searched for possible gamma-ray counterparts of Calvera in the catalogue of gamma-ray sources (Abdo et al. 2010b) detected by the LAT pair-production detector on board the Fermi Gamma-ray Space telescope (Atwood et al. 2009), and in the AGILE gamma-ray bright source catalogue (Pittori et al. 2010). No entries (spatial detections) in the gamma-ray catalogues are compatible with the X-ray source position within $3\sigma$ errors.

Nevertheless, it was worth performing a timing analysis on the LAT data, since the search for source timing signatures can be more sensitive than the spatial analysis to detect and evaluate the flux of weak periodic sources (see e.g. the case of PSR B1509-58 [Abdo et al. 2010a], though typically giving higher statistical errors on the flux. In order to perform gamma-ray timing analysis we retrieved the available LAT public data on Calvera (photon data and spacecraft data) through the Fermi Science Support Center (FSSC) web data-server interface.

We selected only events with high probability of being photons ("diffuse" event class=3, data quality=1) collected within 1-2 degrees around pulsar position; Abdo et al. (2010b). We selected E>100 MeV events extracted within the “region of interest” (ROI) of 2 degrees from X-ray source position (S/N ratio of Fermi-LAT pulsars is typically maximised taking ROI of ∼1-2 degrees around pulsar position; Abdo et al. 2010a). We performed LAT standard data processing using GTSELECT, GTMKTIME and GTBARY tools obtained from the HEADAS distribution of the Fermi Science Tools (version v9r15p2) built on Scientific Linux 5 64 bit operating system. We selected E>100 MeV events extracted within the “region of interest” (ROI) of 2 degrees from X-ray source position (S/N ratio of Fermi-LAT pulsars is typically maximised taking ROI of ∼1-2 degrees around pulsar position; Abdo et al. 2010b).

No significant variations have been detected between the two observations (see Figure 5). The signal shape is almost sinusoidal with pulsed fractions of $18\pm3\%$ (90% confidence, defined as $(C_{\text{max}} - C_{\text{min}})/(C_{\text{max}} + C_{\text{min}})$, where $C_{\text{max}}$, $C_{\text{min}}$ are the maximum and minimum number of counts). The upper limit on the presence of a second harmonic is of the order of 5-7% (3\sigma confidence level).

Finally, we searched for pulsation in the Chandra/HRC-I archive data (obs. ID: 8508) with the aim of obtaining
A grid of gamma-ray frequencies and frequency derivatives was explored with steps oversampling by a factor of 10 the canonical resolution allowed by the data. Weighting the corresponding detection span, the canonical resolution allowed by the data was explored with steps oversampling by a factor of 10. The horizontal dashed line corresponds to $\nu = 0$. See text for details.

A significant pulsed signal from Calvera was detected both by $\chi^2$-test and $Z^2$-test ($\nu = 16.892401975(2)$ Hz, $\nu = -1.2(7) \times 10^{-16}$ Hz$^2$, where $T_{\text{span}}$ is the time span of the data). Pearson’s $\chi^2$ statistics was applied to the 10-bin folded pulse profile resulting from each period search trial. Bin-independent parameter-free $Z^2$-test statistics was also applied to the data.

A reference epoch of 55094 MJD is assumed for the gamma-ray timing analysis. Weighting the corresponding detection probabilities with the number of independent $\nu$ and $\dot{\nu}$ trials ($n_{\text{trials}} \sim 100$) the overall gamma-ray pulse significance is $\sim 3.7\sigma$, corresponding to a fake detection probability of only $3 \times 10^{-4}$. We verified that our analysis procedure does not produce fake detections even considering $\nu$ and $\dot{\nu}$ ranges much larger ($n_{\text{trials}} > 10^4$) than those compatible with the X-rays ephemeris. In obtaining our timing solutions, the position of the source was held at the $\text{Chandra}$ coordinates reported in §3.1.

We have checked that the positional uncertainty ($\sim 1$ arcsec) does not significantly affect barycentric corrections and then the rotational energy variations as a function of energy.

The energy-resolved gamma-ray light curves related to the most significant solution (corresponding to the cross in Fig. 6) are shown in Fig. 7. A single broad peak is detected in the gamma-ray light-curves without significant pulse shape variations as a function of energy.

The pulsed flux was computed considering all the counts above the minimum of the light curve, using the expression $P F = (C_{\text{tot}} - n N_{\text{min}})/\text{Exp} \equiv C_{\text{pul}}/\text{Exp}$, where $C_{\text{tot}}$ is the total number of counts, $n$ is the number of bins in the light curve, $N_{\text{min}}$ are the counts of bin corresponding to the minimum, and $\text{Exp}$ is the exposure in cm$^2$ units. This method is “bin dependent”, but we have checked that different (reasonable) choices of both the number of bins (i.e., $n > 10$) and the location of the bin centre (10 trial values were explored) do not significantly affect the results. The pulsed counts for $E > 100$ MeV are $C_{\text{pul}} = 455 \pm 95$ cts ($C_{\text{pul}} = 275 \pm 75$ for $E > 300$ MeV) corresponding to $\sim 15\%$ of total gamma-ray counts (the unpulsed flux can be ascribed to diffuse gamma-ray background emission). Comparable results are obtained using the the expression adopted for the calculation of the X-ray pulsed fraction $(C_{\text{pul}} - C_{\text{min}})/(C_{\text{max}} + C_{\text{min}})$. No pulsed signal can be significantly ($>3\sigma$) disentangled when data are restricted to narrower ranges in the low energy dipolar braking the upper limit on the magnetic field is $B < 5 \times 10^{18}$ G.

Obviously, tight constraints on the ephemeris will rely on longer data spans. In particular, $>4\sigma$ signal-to-noise ratio on the $\dot{\nu}$ measurements is expected from 1 year of further $\text{Fermi}$-LAT observations.

Figure 6. The $\nu - \dot{\nu}$ contour plot for the gamma-ray timing solutions with $Z$-test significance $>4$ sigma. The most significant detection is $\nu = 16.892401975(2)$ Hz, $\dot{\nu} = -1.2(7) \times 10^{-16}$ Hz$^2$ (timing epoch 55094 MJD). The horizontal dashed line corresponds to $\dot{\nu} = 0$. See text for details.

Figure 7. Energy resolved gamma-ray lightcurves (total counts) taken with $\text{Fermi}$-LAT. The pulsed signal is detected at $\sim 5\sigma$ in the whole $E > 100$ MeV band ($\sim 6$ ms bin resolution). Gamma-ray emission from Calvera seems present at least up to $\sim 1$ GeV though the pulsed signal significance is low at $E > 500$ MeV.
part (e.g. 100-300 MeV), although a modulation (in phase with the profiles obtained from broader energy bands) is still visible in the light curves (Fig. 4). Therefore, only rough gamma-ray spectral measurements can be performed with the present count statistics.

We made a LAT exposure cube from the spacecraft data file using GTLCUBE procedure from Fermi Science Tools and created the exposure map using the GTEXPcube tool. The resulting total exposure of the whole data span at the source position for $E > 100$ MeV is $2.2 \times 10^{39}$ cm$^{-2}$ s$^{-1}$ $5.4 \times 10^{39}$ cm$^{-2}$ s for $E > 300$ MeV), corresponding to $E > 100$ MeV pulsed flux $PF = (4.1 \pm 0.9) \times 10^{-8}$ ph/cm$^2$/s $PF = (6.4 \pm 1.7) \times 10^{-9}$ ph/cm$^2$/s for $E > 300$ MeV). We corrected the pulsed flux accounting for the additional source counts falling outside the ROI (2 degrees radius) estimated according to the instrument Point Spread Function (PSF). We also verified that the pulsed fraction systematic errors due to spectral uncertainties in the exposure calculation are below count statistics errors. A comparison of $E > 100$ MeV and $E > 300$ MeV pulsed fluxes provides a rough gamma-ray photon index estimate $\alpha = 2.5 \pm 0.5$ (100 MeV-10 GeV).

In the frame of a spin-powered pulsar interpretation, the resulting $E > 100$ MeV luminosity, assuming a beaming angle of 1 steradian, is $L_{\gamma} = 1.3 \times 10^{32} d^2_{\text{kpc}} \text{erg s}^{-1}$, where $d_{\text{kpc}}$ is the source distance in kpc. The observed gamma-ray luminosity and the upper limit on the spin-down power ($<10^{33} \text{erg s}^{-1}$) constrain the distance below $\sim 1$ kpc, considering a likely gamma-ray conversion efficiency upper limit of 10%.

3.6 XMM-Newton Pulse phase spectroscopy

In order to look for spectral variations in the X-ray flux of Calvera we first created background subtracted light curves in the energy bands 0.2-0.7 keV and 0.7-2.0 keV and a hardness ratio by dividing the count rates in the hard band by those in the soft band. We used single- and double-pixel events (PATTERN=0-4) from the EPIC pn data, combining both observations and extracted events from the same source and background regions as used for the extraction of the spectra. The light curves were folded with a period of 59.198228 ms, derived from a simple chi-square folding test.

We then investigated the possibility of a changing relative contribution of the two spectral components with spin phase. To this aim, we have produced EPIC pn spectra (MOS1 has insufficient time resolution for pulse phase spectroscopy, PPS) around pulse maximum and minimum (each covering 0.5 in phase) and fitted the four spectra (two observations, two phases) with the double BB model. Similarly to the case of the pulse average spectra, we fitted all the pn spectra simultaneously. We performed fits with two model flavours: models PPS1 and PPS2. In model PPS1 only the relative overall normalisations are allowed to vary between spectra. This corresponds to a case without variation in spectral shape between the two phase intervals. In PPS2 we allow different normalisations for all the BB components, i.e. a variation of the relative contribution of the two blackbody components is possible. The derived spectral parameters and bolometric fluxes are summarised in Table 3 while spectra are shown in Fig. 6. Again, because of no significant long-term flux variations, we only report in the table the fluxes inferred from the pn spectra from the first observation (obs. ID: 0601180101).

Both models assume no temperature changes with pulse phase, and provide a fully acceptable fit. Given the current statistics, we are not in the position to allow more free parameters in the fit or to test different spectral models. As one can see from Table 4 model PPS2 yields a better description of the spectral behaviour with pulse phase (F-test statistic value of 41.3 and chance probability 6.9 $\times 10^{-10}$). This shows that the spectral shape changes with pulse phase, as also indicated by the variations in the hardness ratio (Fig. 6), and suggests that the relative contribution of the hotter component is higher during pulse maximum and lower during minimum.

4 RADIO OBSERVATIONS

Following the discovery of pulsations in the X-rays and gamma-rays, the X-ray position of Calvera was searched for radio pulsations using the Effelsberg telescope with the aim

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6 An efficiency of $\sim 10\%$ is indeed very high, although it may be attained in some sources. As an example, Mignani, Pavlov & Kargaltsev (2010) recently revised the distance of PSR 1055-52, finding a relatively low value of $\sim 300$ pc. This gives a gamma-ray efficiency as high as 10%, in line with the value assumed in this paper.
Table 3. Pulse phase spectroscopy

| Model | $\chi^2$ / d.o.f. | $N_H$ $10^{20}$ cm$^{-2}$ | $kT_1$ eV | $F_{bol1}$ $10^{-13}$ erg cm$^{-2}$s$^{-1}$ | $F_{emin}$ $10^{-13}$ erg cm$^{-2}$s$^{-1}$ | $kT_2$ eV | $F_{bol2}$ $10^{-13}$ erg cm$^{-2}$s$^{-1}$ | $F_{emin}$ $10^{-13}$ erg cm$^{-2}$s$^{-1}$ |
|-------|------------------|--------------------------|---------|----------------|----------------|---------|----------------|----------------|
| PPS1  | 1.17/242         | 4.2±1.0                  | 96±10   | 8.15           | 6.32           | 246±13  | 7.37           | 5.71           |
| PPS2  | 1.01/241         | 4.3±0.7                  | 96±10   | 7.54           | 7.42           | 246±12  | 8.04           | 5.06           |

Bolometric fluxes for the BB components derived from the EPIC pn spectrum of observation 0601180101.

Figure 9. EPIC pn spectra from two different pulse phase intervals covering pulse maximum and minimum from the two XMM–Newton observations. The histograms show the double blackbody model PPS2 as described in the text and Table 3.

of better understanding the nature of the source and in particular, in case of detection, to measure the period derivative given the higher precision generally achievable in the radio band. Observations were taken on MJD 55330 at 1.36 GHz with a bandwidth of 240 MHz spread over 410 frequency channels using a sample time of 55 μs for 78 minutes and for four epochs (a total of 312 minutes). On MJD 55337 a further observation was taken using the same setup for 60 minutes.

These observations were folded using the X-ray ephemeris and searched over a range of frequency dependent time delays to correct for the unknown amount of dispersion (caused by free electrons along the line-of-sight) between Calvera and Earth. These dispersion measures ranged from 0 to 1000 cm$^{-3}$ pc and the step size was optimised for a pulsar with a period of ~ 60 ms. The observations were also searched blindly for any periodicities and for single dispersed pulses (though impulsive radio frequency interferences at Effelsberg make this latter type of search very difficult).

No radio pulses from Calvera were detected down to a sensitivity of $S = 0.05$ mJy for each of the observations assuming a duty cycle of 5%. These observations improved the previous flux density upper limit (obtained by Hossels et al. 2007, with the Westerbork Synthesis Radio Telescope) of almost an order of magnitude (by assuming a spectral index of 1.7, see Kramer et al. 1998). Assuming a distance $d < 1$ kpc, this translates into an upper limit of 0.05 mJy kpc$^2$ for the pseudo-luminosity (defined as $S \times d^2$) at 20cm, a limit that encompasses 99% of all known pulsars (and 100% of the mildly recycled ones to which Calvera could belong, see § 6.2.2) reported in the version 1.40 of the ATNF Pulsar Catalog).

Note that the Effelsberg observations are only sensitive to pulsations and not to continuum emission; inspection of archival NRAO VLA Sky Survey data (Condon et al. 1998) showed no clear evidence of point-like or extended radio sources in the vicinity of Calvera (see § 4).
A non-equilibrium ionisation (NEI) model (Fig. 11), which identifies (Zickgraf et al. 2003). The source catalogue (Voges et al. 1999), but lacks an optical emission region: this detection is included in the bright source detection also located a source within the extended band, but also seen in the 0.5-2.0 keV band. The standard RASS images, where it is best visible in the 0.1-0.4 keV band, but the extended emission is relatively soft and best visible before the combined MOS 0.2-1.0 keV image shown in Fig. 10).

Figure 11. Spectral fit of MOS1/MOS2 data from the extended emission with a NEI model (see text for details).

5 SEARCH FOR DIFFUSE EMISSION IN THE FIELD OF CALVERA

In order to search for possible sources of diffuse emission in the proximity of Calvera, we analysed in detail the XMM-Newton and ROSAT all-sky survey (RASS) images.

Using XMM-Newton MOS1 and MOS2 data, we created colour images for the second XMM-Newton observation. At low energies, different features are clearly visible. North of Calvera we can see an area with increased soft emission, which however shows a sharp edge at the border of the CCD, and therefore it is likely to be related to higher noise in one of the MOS CCDs. More interestingly, the image shows an extended region of soft X-ray emission west of Calvera (at the outer rim of the field of view, where the source detection software also identifies three sources, see the combined MOS 0.2-1.0 keV image shown in Fig. 10). The extended emission is relatively soft and best visible below 1.0 keV.

The extended emission is also clearly seen in the standard RASS images, where it is best visible in the 0.1-0.4 keV band, but also seen in the 0.5-2.0 keV band. The ROSAT source detection also located a source within the extended emission region: this detection is included in the bright source catalogue (Voges et al. 1999), but lacks an optical identification (Zickgraf et al. 2003). The ROSAT images do not show significant emission north of Calvera, confirming that the feature seen in the EPIC image is likely to be due to CCD noise.

Although it is unlikely that the extended emission is related to Calvera, considering their angular separation of 13', it remains an interesting detection. Its X-ray morphology is reminiscent of an old supernova remnant, or a pulsar wind nebula. Further insights on its nature can be obtained by a spectral analysis. Therefore, we extracted the MOS1+MOS2 spectra from an elliptical region (246'' and 117'' semi-axes) covering the extended source. The background was extracted using two circular regions (122''radius), free of XMM-Newton detections (see Fig. 10). Spectra were fitted using a non-equilibrium ionisation (NEI) model (Fig. 11), which reproduces the X-ray spectra of faint SNRs, e.g. in the Magellanic Clouds (see e.g. Filipovic et al. 2008). We found that the spectrum of the diffuse emission is well represented by this model ($\chi^2_r$ = 1.35 for 46 d.o.f.), and clearly shows the (unresolved) emission line triplets of O VII and N VI. From the fit, O appears to be over-abundant by a factor of ~ 2 - 3. Unfortunately, due to the scarce data, the temperature is unconstrained (it has been fixed at 0.7 keV during the fit) and we could only derive an upper limit on the column density, $N_H < 1.5 \times 10^{20}\text{cm}^{-2}$ (3$\sigma$).

In order to investigate further the nature of the extended emission, we inspected the DSS R, B and IR images, but did not find evidence for spatial structures. We also checked for evidence of diffuse $H_\alpha$ emission at the position of the XMM-Newton extended source using images from the The Virginia Tech Spectral-Line Survey (VTSS), which has pixel size of 1'6 and field of view of $10^5 \times 10^5$ per pointing. Unfortunately, the Calvera field is not yet available in the processed Survey data. No other $H_\alpha$ survey data are available, which cover the field with a sufficient spatial resolution.

We then inspected the field in radio continuum using data from the NRAO/VLA Sky Survey (NVSS) at a frequency of 1.4 GHz, which covers the sky at $\delta > -40^\circ$ with beams of 45'' FWHM (Condon et al. 1998). From the NVSS data (Fig. 12) we could not find evidence for any radio source, either point-like or extended, at the position of Calvera, down to a flux level of ~ 0.1 mJy (3$\sigma$) at 1.4 GHz. As far as the radio emission from Calvera itself is concerned, this upper limit is much less constraining than those discussed in §2. The closest radio source detected in the NVSS data is located at ~ 30'' from the position of Calvera, it is not extended and has an estimated flux of ~ 0.47 mJy. At the same time, we found about a dozen radio sources (~ 0.5 - 2.5 mJy) within a circle of 5' radius centred on the position of the X-ray extended emission. However, none of them shows evidence of extended radio emission on angular scales larger than ~ 2'. We could not find evidence of diffuse emission over the whole searched area down to a limit of $\sim 1.5 \mu J\text{arcsec}^{-2}$, which we assume as the upper limit on the radio brightness of the extended emission detected in the XMM-Newton and ROSAT data.

6 DISCUSSION

We have presented a new multi-wavelength study of the NS candidate Calvera (1RXS J141256.0+792204), based on two new XMM-Newton observations, on one set of publicly available Fermi-LAT data and on one new observation taken at Effelsberg in the radio band. We also used Chandra and ROSAT archival data. We discussed previous determinations of the source position, and concluded that at present the best estimate is that based on absolute Chandra ACIS-S astrometry, i.e. $\alpha = 14^h12^m55.84, \delta = 79^\circ22'03.7''$ with a 90% confidence error of 0'.6.

The combination of XMM-Newton and Fermi-LAT has allowed us to discover the period of the source, $P \approx 59.19$ ms, and to place an upper limit on its spin-down

7 http://www.atnf.csiro.au/research/pulsar/psrcat/

8 http://www.phys.vt.edu/ halpha/
rate, |\ddot{P}| < 5 \times 10^{-18} \, \text{s}^2 \, \text{s}^{-2}. We warn that positive frequency derivatives cannot be excluded, although, based on the contours presented in Fig. 6 they appear to be less likely. This possibility will be addressed by future timing monitoring, and will not be discussed further hereafter. Instead, in case of spin-down our measurements correspond to a rotational energy loss \dot{E}_{\text{rot}} < 10^{33} \, \text{erg} \, \text{s}^{-1}, a large characteristic age \tau > 1.55 \, \text{Gyrs}, and a low magnetic field, \emph{B} < 5 \times 10^{10} \, \text{G} (under the assumption of magneto-dipolar breaking).

Although the best-fit of the X-ray spectrum is not unique (see Table 2), according to our findings (see §5.1 for a detailed discussion), the most likely spectral model consists of two thermal components (blackbodies) with temperatures \emph{kT}_1 \sim 150 \, \text{eV}, \emph{kT}_2 \sim 250 \, \text{eV}, plus possibly an absorption edge at \sim 0.65 \, \text{eV} (\sim 0.65(1+z) \, \text{eV} when measured at the star surface). Similar spectral features are found in other classes of thermally emitting NS, as the XDINSs (see e.g. Turolla 2003, and references therein) or 1E 1207.4-5209 (e.g. Bignami et al. 2003, Mori & Hailey 2004), which, however, are characterised by a much larger spin period. By interpreting the edge as an electron or a proton cyclotron feature gives \emph{B} = 6 \times 10^{12} (1+z) \, \text{G} or \emph{B} = 6 \times 10^{13} (1+z) \, \text{G}, respectively: the former value is not too different from the limit inferred from the timing (which, however, only constrains the large scale dipolar component). Instead, we do not find substantial evidence for the emission line at \sim 0.5 - 0.6 \, \text{keV} proposed by Shevchuk, Fox & Rutledge 2009); on the other hand, considering the thermal character of the underlying continuum, a feature in absorption appears a more likely outcome. The X-ray luminosity is \emph{L}_X \sim 10^{32} \, \text{d}^2_{\text{kpc}} \, \text{erg} \, \text{s}^{-1} (\text{with small variations depending on the assumed spectral model, see Table 2}), and there is no evidence for a PL tail up to a flux contribution of \sim 10\%.

Overall, Calvera is a very puzzling pulsar. It has a thermal soft X-ray spectrum (with a possible absorption feature), but, at variance with other similar sources as the XDINSs, it is not a “soft” source: through our timing search we found that it is still detected at > 4\sigma even at \emph{E} > 300 \, \text{MeV}. A rough estimate of the 100 \, \text{MeV}-10 \, \text{GeV} photon index gives \emph{\alpha} = 2.5 \pm 0.5. The gamma-ray luminosity is \emph{\dot{L}}_{\gamma} = 1.3 \times 10^{32} \, \text{d}^2_{\text{kpc}} \, \text{erg} \, \text{s}^{-1}, computed by assuming a beaming angle of 1 \text{steradian}. Assuming a gamma-ray conversion efficiency upper limit <10\%, and assuming that the observed gamma-ray luminosity is powered by spin-down, the upper limit on the rotational energy loss (< 10^{33} \, \text{erg} \, \text{s}^{-1}) provides a quite strong constraint on the distance, that turns out to be below \sim 1 \, \text{kpc} (much lower distances might result from the future estimate of the true value of \dot{E}_{\text{rot}}).

The source is not detected in the optical and radio bands. Based on the non detection of the source on a Gemini-North+GMOS imaging of the field, Rutledge, Fox & Shevchuk 2008 reported a 3\sigma upper limit of \emph{g} > 26.3 \, \text{mag}, or \emph{\dot{P}} < 0.11 \, \text{µJy}, at 4750 \, \text{Å}. As for the radio band, our Effelsberg observation allowed us to set a deep upper limit on the source pulsed emission of 0.05 \, \text{mJy}, assuming a duty cycle of 5\%.

Finally, we report evidence for diffuse X-ray emission in the field of Calvera, \sim 13' west of the source.

In the following, we will first discuss the spectral and timing results, and then we will elaborate on the implications of our new findings regarding the perspectives on the source interpretation.
Thanks to the high sensitivity of XMM–Newton at low energies, we have been able to reach a good characterisation of the X-ray spectrum. In agreement with previous findings based on Chandra data (Shevchuk, Fox & Rutledge 2009), we found that the X-ray spectrum can not be reproduced by a single component model, while a satisfactory fit can be obtained by adding a spectral feature to an atmospheric model (NSA). This spectral decomposition has the advantage that it requires a relatively low value of interstellar absorption ($N_H \approx 2.6 \times 10^{20}$ cm$^{-2}$), compatible with that inferred from HI maps in the source direction (Kalberla et al. 2003; Shevchuk, Fox & Rutledge 2009). In this case, the star surface emits at a uniform temperature of $\sim 100$ eV, and the feature is more likely to be an absorption edge at $\approx 0.65(1 + z)$ keV.

The main problem with a scenario based on uniform surface emission is that our measurement of a relatively large X-ray pulsed flux ($PF \sim 18\%$) seems to rule out a relatively smooth thermal map. Pulse profiles produced by the thermal surface distribution induced by a simple core-centered dipolar magnetic field have been investigated long ago by Page (1993), under the assumption that the surface emits (isotropic) blackbody radiation. Because of gravitational effects and of the smooth temperature distribution (the temperature monotonically decreases from the poles to the equator), the pulse modulation is quite modest ($PF \lesssim 10\%$).

Indeed, our spectral fits show that the spectral decomposition is not unique: an equally likely possibility is that the spectrum is made of two thermal components (again with possibly a spectral feature at $\sim 0.6 - 0.7$ keV), reflecting the presence of two zones of the NS surface at different temperatures. The two components can be modelled either with a NSA or a BB, with the difference that, since atmospheric models are harder than a blackbody at the same temperature, the temperatures inferred from a NSA+NSA fit are systematically lower than those obtained from a double BB model. As a consequence, a BB+BB and a NSA+NSA decomposition result in very different predictions for the amount of flux expected in the optical band (see for example Fig. 13), and in principle it may be possible to use optical observations to discriminate between the two options. Unfortunately, in practice, this is unfeasible. The $g$-band upper limit from the Gemini-North+GMOS imaging translates into $\approx 1.5 \times 10^{-4} \text{ keV cm}^{-2}\text{s}^{-1}\text{keV}^{-1}$ at $\approx 2 \times 10^{-3}$ keV, which is still compatible even with the large fluxes expected in the atmospheric emission scenario (see Fig. 13 right panel). In order to use this approach to robustly discriminate among X-ray spectral models, we would need an upper limit on the optical flux at least 1-2 orders of magnitude lower, which requires deep imaging of the field down to $g \sim 29 - 31$. This is clearly unfeasible with the current instrumentations.

### Table 4. Radii of the emitting regions and source distance inferred from the spectral modelling with two thermal components.

| Model | $N_H$ | $R_{\text{cold}}/R_{\text{hot}}$ | Distance | Comment |
|-------|-------|-------------------------------|-----------|---------|
| BB + BB free | 3.1 / 0.43 | $N_H > N_{\text{gal}}$ |
| BB + BB fixed | 1.9 / 0.36 | $N_H > N_{\text{gal}}$ |
| (BB + BB)$\times$edge fixed | 1.6 / 0.36 | $N_H > N_{\text{gal}}$ |
| NSA + NSA free | 175 | 1550 |
| NSA + NSA fixed | | 2250 |

Figure 13. Left panel: The best-fitting double blackbody model shown in Fig. 2 (left panel) extrapolated in the optical band. Red lines: hot component, blue lines: cold component, black lines: total. Solid and dashed-dotted lines correspond to absorbed and unabsorbed spectra. The arrow marks the $g$-band upper limit inferred from Gemini-North+GMOS imaging (see text and Rutledge et al. 2008). Right panel: Same as in the left panel for the NSA+NSA model shown in the right panel of Fig. 2.
In this respect, some insights may be obtained exploiting the detection of the source at high energy based on the LAT timing analysis. In fact, the fits to X-ray data with two thermal components using a NSA+NSA or a BB+BB model result in different estimates of the distance and of the size of the emitting regions (see Table 4). In Table 4 we report the predicted distances inferred by the fits based on a double NSA model, for the limit case of the colder component emitted from the whole NS surface. This is an overestimate for the area of the colder region, since a second, hotter NSA component is present. However, the ratio of the cold/hot areas is \( \approx 0.02 - 0.05 \) (similar to that implied by the BB+BB fit), and our estimates of the distance would not change significantly by assuming that \( \approx 95\% \) (instead of 100\%) of the whole surface is emitting at the lowest temperature. In this case, if \( N_H \) is fixed at a value compatible with the Galactic absorption, the distance turns out to be quite large, \( \sim 1.5-2 \) kpc, which seems too large when compared with the limit inferred from the gamma-rays (unless the gamma-ray conversion efficiency is extremely high). Similarly, the BB+BB model is only compatible with emission from the whole surface (from the coldest component) if the star is at 5 kpc or more, which, again, contradicts the gamma-ray limit.

In fact, a BB+BB model is compatible with the relatively large PF only for \( d \sim 1 \) kpc, which gives quite small BB radii (\( \sim 0.5 - 3 \) km) suggesting a scenario in which the two thermal components originate in two different small spots at the star surface. If this is the case, the rather small emitting areas, together with a pulsed fraction of \( \sim 18\% \), and the sinusoidal pulse shape, are suggestive of a geometry in which the star is a quite aligned rotator seen at a large inclination angle. This is also supported by the pulse-phase spectroscopy and hardness ratio variation, which indicate that there is only a moderate spectral evolution with phase. This may be explained if both emitting caps are always (partially) in view as the star rotates, with the hotter spot becoming more visible near the pulse maximum. The gamma-ray pulses are also quite sinusoidal, with no evidence for changes at different energies and a pulsed fraction similar to that in the X-rays. However, the current impossibility of phase-align the X- and gamma-ray observations (see §4.3 for all details) prevents to reach any conclusions on the relative positions of pulse maxima.

6.2 The nature of the source

Our new findings, in particular the new discovery of the X-ray and gamma-ray period and the measurement of an upper limit for the spin-down rate, unequivocally identify Calvera as a relatively fast spinning NS, and provide long-sought crucial information to shed light onto the conundrum about its nature (see below and §2). Based on the preliminary spectral informations available at that time, Rutledge, Fox & Shevchuk (2008) attempted to classify Calvera by comparing it with different classes of compact objects that occupy different regions in the luminosity/effective temperature/emitting radius spaces. In light of the new discovery of a relatively fast period, some of the previously proposed scenarios as that of an XDINS or a magnetar are now ruled out. Similarly, Calvera’s spin period is too large to be compatible with an interpretation in terms of a (fully) recycled millisecond pulsar.

In the context of the \( P - \dot{P} \) diagram, Calvera appears as one of the transition objects that populate the zone between the bulk of the pulsar crowd and the group of recycled millisecond pulsars (in the bottom-left corner of Fig. 14). Also, the rotational parameters (hence the values of \( E \) and \( B \)) are consistent with those of the CCOs, the most similar of which is the source in Kes 79.

These findings, taken together with the fact that the source is apparently isolated and it is not associated with a SNR (but see §0.2.1), open exciting novel possibilities, among which the most likely are that of an “orphan CCO” or that of a mildly recycled source that was once member of a high mass binary system (see §6.2.1 & 6.2.2).

6.2.1 A new CCO?

Based on the timing properties and on the thermal character of the spectrum, a first possibility is that Calvera is a new CCO. In this respect, we note that the X-ray energetics of the source is also unusual. The upper limit on \( E_{\text{rot}} \) \( (< 10^{33} \text{ ergs}^{-1}) \) is only a factor of 10 larger than the X-ray luminosity inferred from \( XMM-\text{Newton} \) data \( \sim 10^{32} \text{ ergs}^{-1} \text{ at 1 kpc} \). While an efficiency of \( \sim 10\% \) in gamma-ray is not unusual (see §3.5), the conversion efficiency in the X-ray band is typically lower, of order of \( \sim 10^{-2} - 10^{-3} \) (Becker, Huang & Prinz 2010). If the X-ray emission if powered by the source spin-down (for instance in the case in which it originates from two hot spots at the star
surface, heated by back-flowing magnetospheric currents), a similar efficiency would imply a very low distance, of order of \( \sim 100 \sim 300 \) pc (or even less, considering that our estimate of the upper limit on \( E_{\text{rot}} \) is conservative). Alternatively, the thermal X-ray emission may have a different origin (e.g. anisotropic surface cooling). In this case we note that, based on our spectral fitting, we cannot exclude that a \( \sim 10\% \) of the X-ray flux is ascribed to a non thermal PL component; if this fraction of the total X-ray emission is spin-down powered, an efficiency of \( 10^{-2} \) translates in \( d \sim 1000 \) pc.

Interestingly, apart from binary systems and magnetar sources, that are thought to be powered, respectively, by accretion or by the super-strong magnetic field, the only sources that may be characterised by \( E_{\text{rot}} \lesssim L_X \) are the (slowly rotating) XDINSs (Kaplan & van Kerkwijk 2000) and the CCOs. For instance, the only CCO for which the spin period derivative has been (recently) measured (i.e. PSR J1852+0040 in Kesteven 79, see Halpern & Gotthelf 2010), has \( L_X \sim 10 E_{\text{rot}} \). In all other cases only an upper limit on the period derivative is available; still, 1E 1207.4-5209 has \( L_X \sim 2 \times 10^{33} \) erg s\(^{-1}\) and \( E_{\text{rot}} < 10^{32} \) erg s\(^{-1}\) (Gotthelf & Halpern 2007). Puppis A has \( E_{\text{rot}} < 10^{33} \) erg s\(^{-1}\), that does not exclude an efficiency of \( \sim 10^{-2} \) (Gotthelf & Halpern 2009). The X-ray emission of CCOs is thermal and characterised by a double black body spectrum, without the presence of hard X-ray tail, similar to the X-ray spectrum Calvera.

A possible counter-argument for the CCO interpretation might be raised by comparing with Fig. 2-3 by Rutledge, Fox & Shevchuk (2008): Calvera’s surface temperature is quite low with respect to those typically observed in this class, and, since the typical X-ray luminosity of other CCOs is \( \sim 10^{33} \) erg s\(^{-1}\), this interpretation would require a source distance of 2-3 kpc (against the constraint from the gamma-rays). Nevertheless, we warn that these problems with a CCO interpretation may be not too severe. The comparison of Calvera with CCOs based on the temperature comes with caveats, since it does not account for the fact that different CCOs might have different ages, or that the thermal history of a CCO might have been modified by a recent phase of accretion. Also, we note that the derived CCO luminosities are based on the estimated distances of the host SNRs, which are usually affected by uncertainties of the order of \( 50\% \) or more. Thus, using CCO luminosities as standard candles could be risky.

The possible association with a SNR, or lack thereof, is a crucial piece of information to determine whether Calvera is, or not, a CCO. We already noticed that the extended X-ray source detected west of Calvera in the \( \text{XMM-Newton} \) and \( \text{ROSAT} \) data shows evidence for triplets of O VII and N VI in the spectrum, which are robust signatures of SNRs (although a final confirmation could only come from H\(\alpha\)/S II/O III ratios). If we assume that Calvera has moved 13’ away from the centre of this putative SNR, the kinematic age of Calvera (and in turn the age of the SNR) results \( t = 39000 v_{100}/v_{100} \) yrs, where \( v_{100} \) is the source velocity in units of 100 km s\(^{-1}\). This is much lower than the 1.55 Gyr age estimated from the spin parameters. However, this is a common characteristic of CCOs: the lower limits on their spin-down ages (although smaller than that of Calvera) are always much larger than the SNR ages. A way out, within the “anti-magnetar” interpretation (Halpern & Gotthelf 2010), is to assume that the initial spin periods of these pulsars were very close to their current values, so that they have not changed much during the pulsar’s lifetime. In other words, the spin-down age is not representative of the true age of the source but only reflects its initial conditions at birth.

Despite these considerations, we consider it unlikely that this extended emission is associated to Calvera. At a distance of \( \sim 1 \) kpc a typical CCO-associated SNR is expected to be much larger: for instance the 7 kyr old SNR associated to 1E 1207.4-5209 would appear with an angular size of \( \sim 2\arcmin /d_{\text{kpc}} \). Instead, the size of the extended emission derived from the \( \text{ROSAT} \) contours is \( 16’ \times 8.5’ \), which suggests that the SNR is a background object. We note that the upper limit on the column density inferred from the SNR spectrum (\( N_H < 1.5 \times 10^{20} \text{cm}^{-2} \)) is smaller than the Galactic \( N_H \) in the direction of Calvera. This would make the extended emission likely closer, however this comparison is hampered by the limited photon statistics of the diffuse source. Considering the angular separation and the low \( E_{\text{rot}} \) of the pulsar, it is also unlikely that the extended source is a pulsar wind nebula associated to Calvera.

On the other hand, if Calvera is an underluminous CCO at a low distance of only \( \sim 300 \) pc, the large spatial scale would make it hard to detect the SNR with narrow field X-ray instruments like EPIC. Furthermore, it can not be ruled out that Calvera is an old (> 1 Myr) CCO and that its host SNR has already expanded and faded away in the interstellar medium.

This “orphan CCO” scenario is potentially intriguing, especially in view of the possible connections between old CCOs and other NS classes. Still, in this scenario Calvera would be a quite extreme case. So far, no CCO has been detected at gamma-ray energies. This may be due to observational limits: firstly, in cases in which the embedding SNR dominates it is difficult to resolve the gamma-ray emission from the CCO. Secondly, detecting CCOs as weak gamma-ray pulsars is difficult because only three of these sources have an X-ray period and only one (Kes 79) has a measured \( P \). In Fig. 15 we report the ratio \( E_{\text{rot}}/d^2 \) (a often used figure of merit for the detectability in the gamma-ray band of a source with \( E_{\text{rot}} < 10^{34} \) erg s\(^{-1}\); e.g. [Abdo et al. 2010a]) plotted against the spin period for various relevant samples of neutron stars (see caption of Fig. 15). As we can see, among the CCOs with a measured (or an upper limit value of) \( P \), two of them have a relatively low value of \( E_{\text{rot}}/d^2 \), which may hamper the gamma-ray detection. Would a CCO nature be confirmed, Calvera will represent a unique case and our timing technique, here applied to \( \text{Fermi} \) data, constitute a key tool to investigate the high energy spectrum of other members of the class (the most promising candidate for this search being Puppis A, whose upper limit for \( E_{\text{rot}}/d^2 \) is, as in the case of Calvera, compatible with relatively a large value).

### 6.2.2 Is Calvera the first discovered mildly recycled gamma-ray pulsar?

The spin period and the upper limit on the spin period derivative place Calvera well within the area of the \( P - \dot{P} \) diagram which is known to be populated by the so called mildly recycled radio pulsars. Hence the plausible and very
intriguing possibility that Calvera represents the first case ever of a mildly recycled gamma-ray pulsar.

It is commonly believed that recycled radio pulsars are formed when a relatively old neutron star is spun up by accretion while in a binary system (Bisnovatyi-Kogan & Komberg 1974). The amount of mass accreted, hence of spin up, is related to the duration of the X-ray binary phase, and ultimately depends on the mass of the companion: low mass X-ray binaries are thought to be the progenitors of the so called “fully” recycled radio pulsars (often referred to as millisecond radio pulsars), whereas high mass companions give rise to mildly recycled radio pulsars with periods of tens of ms (e.g. Lorimer et al. 2004).

In this picture we note that the lack of a detection of Calvera in the radio band (down to a very deep flux density limit) can be plausibly explained by the relatively narrow radio beam missing the Earth. As to the X-ray luminosity, one can apply similar considerations to those reported for the CCO hypothesis (see § 6.2.1), i.e. a rotation-powered nature requires a distance as low as $\sim 100 \sim 300$ pc. The double BB X-ray spectrum, however, is somehow unusual for a recycled pulsar, since most of them are characterised by either single component (either BB or PL) or BB+PL spectra.

The observability in the gamma-ray band is an unprecedented feature for NSs with the rotational parameters of Calvera and one may wonder if it is due to some peculiarity in the gamma-ray emission process operating in this source or to observational biases. In this respect we first note that, provided the distance is around or below 300 pc, the gamma-ray efficiency nicely fits with the average value (around few percent) seen in the gamma-ray pulsars observed by Fermi-LAT. Even assuming a larger distance of 1 kpc, the gamma-ray efficiency remains compatible with what observed in at least one other object (Mignani, Pavlov & Kargaltsev 2010). Also, the gamma-ray spectrum is within the range of those shown by the Fermi pulsars, although pointing toward the tail of the steepest spectral indices in the spectral parameter distribution. By inspecting Fig. 15, we can see that the large majority of the NSs with rotational parameters in the range of those of the mildly recycled radio pulsars (empty dots in the diagram) have a $E_{\text{rot}}/d^2$ ratio well below the minimum value which resulted in a detection with Fermi-LAT. Even assuming a larger distance of 1 kpc for the source, we note that in principle its $E_{\text{rot}}/d^2$ ratio can be at least 10 times larger (for a distance less than 300 pc) than that of the best cases among the mildly recycled radio pulsars (similar results hold when plotting the analogous parameter $\sqrt{E_{\text{rot}}/d^2}$, e.g. Abdo et al. 2010a).

In this plot, we might still find a mild rotation-powered process operating in this source or to observational biases. In this respect we first note that, provided the distance is around or below 300 pc, the gamma-ray efficiency remains compatible with what observed in at least one other object (Mignani, Pavlov & Kargaltsev 2010). Also, the gamma-ray spectrum is within the range of those shown by the Fermi pulsars, although pointing toward the tail of the steepest spectral indices in the spectral parameter distribution. By inspecting Fig. 15, we can see that the large majority of the NSs with rotational parameters in the range of those of the mildly recycled radio pulsars (empty dots in the diagram) have a $E_{\text{rot}}/d^2$ ratio well below the minimum value which resulted in a detection with Fermi-LAT. Even assuming a larger distance of 1 kpc for the source, we note that in principle its $E_{\text{rot}}/d^2$ ratio can be at least 10 times larger (for a distance less than 300 pc) than that of the best cases among the mildly recycled radio pulsars (similar results hold when plotting the analogous parameter $\sqrt{E_{\text{rot}}/d^2}$, e.g. Abdo et al. 2010a). Therefore, in the framework of the interpretation of Calvera as a mildly recycled gamma-ray pulsar (for which a large distance is largely preferred), it seems that the relativistic large observed gamma-ray flux of Calvera is due to its proximity rather than to a stronger intrinsic emission with respect to the other known rotation powered neutron stars.

It is worth noting that the relatively steep gamma-ray spectral index of Calvera could be echoed in the spectrum of the mildly recycled pulsar in the Double Pulsar binary (PSR J0737−3039A, Burgay et al. 2003; Lyne et al. 2004). For the latter (whose $E/d^2$ is also very promising, see Fig. 15 there is a tentative detection with Agile-GRID (Pellizzoni, in preparation) and no detection so far with Fermi-LAT, which would indicate a very soft gamma-ray spectrum (interestingly enough, also the X-ray spectrum of the Double Pulsar appears unusually soft among the recycled pulsars, Pellizzoni et al. 2008, Possenti et al. 2008). If confirmed by future analysis, this may be a peculiarity of the high energy emission from the class of mildly recycled pulsars.

As to the evolution of Calvera, the presence of a main period rules out the millisecond radio pulsar scenario proposed by Rutledge, Fox & Shevchuk (2008).
sequence, or a giant or a white dwarf companion can be ruled out by the deep optical upper limit. This in turn suggests that Calvera is not the descendant of an intermediate-mass X-ray binary, since the end products of these systems usually comprise a neutron star orbiting a heavy Carbon-Oxygen white dwarf or (in some peculiar cases, see e.g. [1]) a Helium white dwarf. Given the considerations above, it seems very likely that Calvera was recycled in a high-mass X-ray binary, in which also the companion star eventually experienced a supernova explosion. The most probable outcome of this event is the disruption of the binary, with the release of two isolated neutron stars, one having the typical parameters of a ordinary pulsar and the other - usually dubbed disrupted recycled pulsar, DRP (i.e. see [2]) - having a moderate spin rate (in the range of few tens of ms) and a surface magnetic field which is intermediate between that of the ordinary pulsars and that of the fully recycled pulsars. Alternatively, there is the possibility that the binary system survives the supernova explosion, leading to the formation of a double neutron star (DNS) binary. If the absence of a binary companion will be supported by future dedicated campaigns of observation, Calvera will enter the rare class of the DRPs, which would make its discovery particularly worthwhile for investigating various still open issues on the final stage of the evolution of high-mass X-ray binaries and on the supernova kick.

For instance, there is currently a large mismatch between the theoretical expectations on the relative number of DRPs and DNSs and the result of the observations. According to the fact that the survival of the binary in the second supernova explosion requires properly tuned parameters for the pre-supernova system and/or for the kick associated to the supernova event, population synthesis studies (e.g. [3]) indicate that DRPs are expected to be generated at a significantly higher rate than DNSs. Since the rotational parameters of the NSs are similar in the two classes of objects, their lifetime in the radio band and their radio emission properties should also be similar and hence one would expect to detect up to ~10 times more DRPs than DNSs ([4]). At variance with this prediction, to date 8 DRPs in the Galactic field are reported, a number matching that of the 8 known DNSs (from ATNF pulsar catalog at 30 June 2010). Supernova kicks smaller than those usually assumed in population synthesis have been proposed to at least partially alleviate this problem: in fact that would reduce the gap between the birth-rates of the DRPs and that of the DNSs.

Notably, the distances (derived from the dispersion measure) of the known DRPs (all selected in the radio band) cluster mostly between 2 and 3 kpc, with the closest source (PSR J2235+1506) located at 1.2 kpc. Therefore, Calvera would turn out to be much closer than all the other DRPs, suggesting the existence of a significant (if not even dominant) contribution of the gamma-ray pulsars to the population of the mildly recycled neutron stars. Were this the case, the current observed ratio between the number of radio selected DRPs and DNSs could not be representative of the whole population. Of course, additional discoveries of mildly recycled gamma-ray pulsars (with particular emphasis for blind searches), as well as detailed binary pulsar population synthesis models are necessary to assess the biases due to the small-number statistics and to properly test the aforementioned hypothesis. The confirmation of a DRP interpretation for Calvera and the discovery of similar sources would have strong implications: e.g. it will impact on the estimates of the beaming factor (i.e. the fraction of sky swept by the emission beam(s)) in the radio and gamma bands for the mildly recycled neutron stars, thus constraining their emission models; it will lead to increase the overall birth-rate of the descendants from high-mass X-ray binaries in the Galaxy; it will also suggest the existence of some DNS binary at close distance from the Earth and which escaped radio detection so far. This may in turn lead to an upward revision on the expected rate of events of merging of DNSs in the Galaxy, a key prediction for the current generation of ground-based gravitational wave detectors.

Once the spin down rate (and hence the surface magnetic field) of Calvera will be measured it might be possible to estimate its initial spin period (post spin-up phase, see Fig. 2 in [5]) - as well as the time since the occurrence of the second supernova explosion in the progenitor binary. With the present data we can only notice that, in both the DRP and DNS hypotheses, Calvera is expected to be much younger than the age inferred from the spin-down rate ([6]; e.g. for our upper limit on $P$, the time elapsed from the second supernova would be $10^6$ yr, under the hypothesis that Calvera was spun up by accretion of mass at the Eddington rate up to the limit imposed by its magnetic field. ([7]). Since the position of Calvera - slightly outside the Galactic disk, at a distance $<0.6d_{kpc}$ above the Galactic plane - could be ascribed to the kick imparted to the neutron star (or to the DNS binary) by the second supernova, a constraint on the time since the explosion (even better if complemented with constraints on the proper motion of the source) will in turn allow one to study the kick imparted to the neutron star (or to the DNS binary) in the supernova.

7 CONCLUSIONS

Thanks to our multi-wavelength campaign, we have been able to recognise in Calvera an intriguing, low magnetised pulsar with a relatively fast period, $\sim 59$ ms. This rules out most of the previously proposed scenarios for the nature of the source. Calvera’s properties are reminiscent of those of CCOs and mildly recycled pulsars, although other interpretations can not be ruled out (mainly because our timing solution is still compatible with a spin up scenario). On the other hand, even in comparison with the other members of these two classes, the source can be singled out thanks to its unique characteristics, mainly the hard gamma-ray emission joined to a thermal X-ray spectrum.

The discovery of peculiar, possibly transitional, sources such as Calvera is of the utmost importance to gain a full understanding of the Galactic NS phenomenology and to eventually establish links between the different classes into which isolated NSs have been catalogued up to now. The existence of bridging objects is progressively coming into

\[10 \text{ Our present data do not allow us a search for orbital period-}\]
view, as in the case of PSR B1509-58 for the magnetar/high-field spin-powered PSRs connection (Pellizzoni et al. 2009), of the newly discovered radio magnetar (Levin et al. 2010), or the bursting young pulsar PSR J1846-0258 (Gavriil et al. 2008). Furthermore, although Calvera is most likely to be isolated, the current optical limits do not allow us to exclude a NS companion, in which case the source would represent one of the rare DNS systems discovered in the Galaxy.

Given the unique placement of Calvera in this framework, further investigations aimed at better assessing its properties are definitely warranted. Accurate X-ray timing can provide a positive determination of the source spin-down rate, and a better characterisation of its spectrum, especially concerning the presence of a high-energy PL tail and of spectral features, is bound to reveal much on the processes which power its X-ray emission, and ultimately on its true nature. Presently we were able only to place an upper limit on the pulsed radio flux. Calvera may be genuinely radio quiet but the search for radio emission must be pursued further since a detection at radio wavelengths would yield an independent, accurate determination of \( P \), the dispersion measure and the star proper motion (the latter may be also pursued in the X-ray band, see Shevchuk, Fox & Rutledge 2009). Follow-up X-ray and optical narrow-band imaging observations will allow one to better characterise the properties of the putative SNR, and to constrain both its age and distance. All these issues are crucial to assess if there is indeed a connection between Calvera and the nearby diffuse emission, the presence of which was first reported in this investigation. New observations at gamma-ray energies will allow one to better constrain the source spin evolution, shed light on the spectral distribution at gamma-ray energies and how the latter changes with rotational phase. Finally, the search for gamma-ray emission from other sources with similar properties (CCOs, mildly recycled and low \( E_{\text{tot}} \) PSRs, ...) using the novel timing technique which led us to the detection of Calvera in the gamma-rays is certainly in order and will be matter of future work.

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