THE PECULIAR NEUTRON STAR CALVERA THROUGH WAVEBANDS*

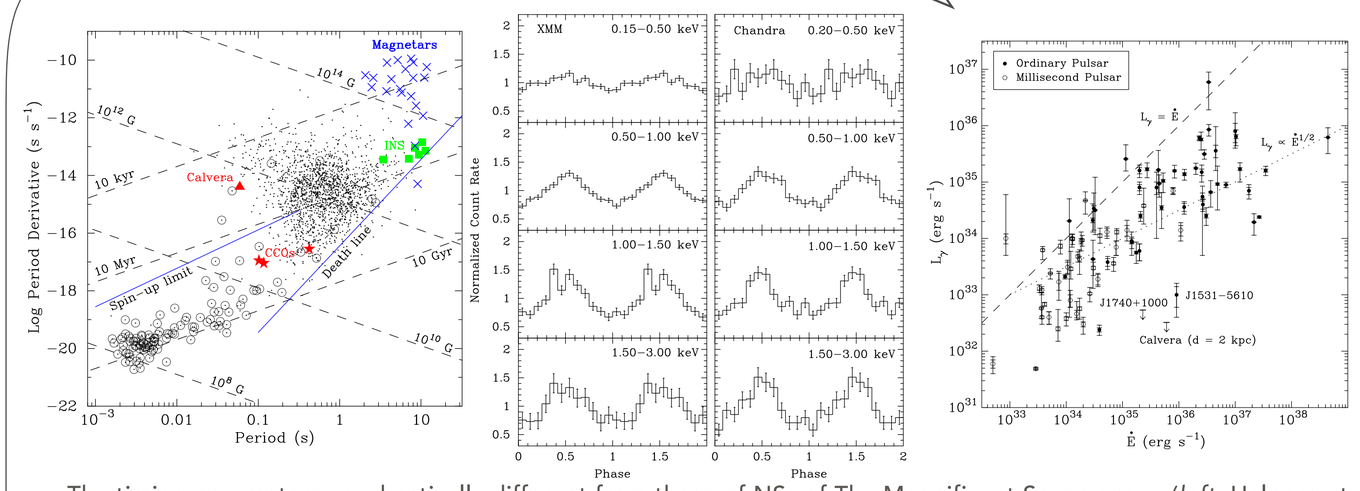
Yury Shibanov, **Andrey Danilenko****, Sergey Zharikov, Peter Shternin and Dmitry Zyuzin

(All from Ioffe Institute, except for Sergey Zharikov, who is from UNAM, Mexico)

Abstract

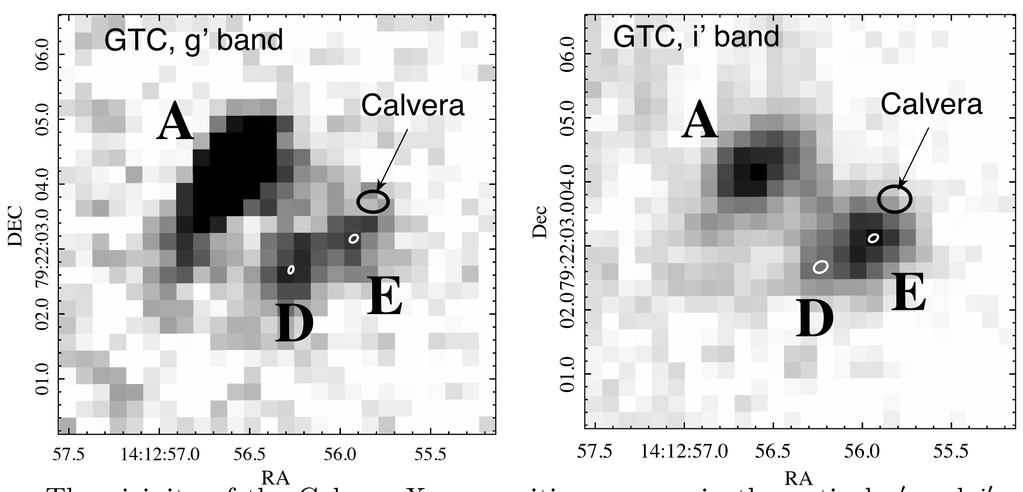
Calvera is an unusual isolated neutron star with pure thermal X-ray spectrum typical for central compact objects in supernova remnants. On the other hand, its rotation period and spin-down rate are typical for ordinary rotation-powered pulsars. It was discovered and studied in X-rays and not yet detected in other spectral domains. We present deep optical imaging of the Calvera field obtained with the Gran Telescopio Canarias in g' and i' bands. Within $\approx 1''$ vicinity of Calvera, we detected two point-like objects invisible at previous shallow observations. However, accurate astrometry showed that none of them can be identified with the pulsar. We put new upper limits on its optical brightness of $g' > 27.87$ and $i' > 26.84$. 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.

What had been known about Calvera before



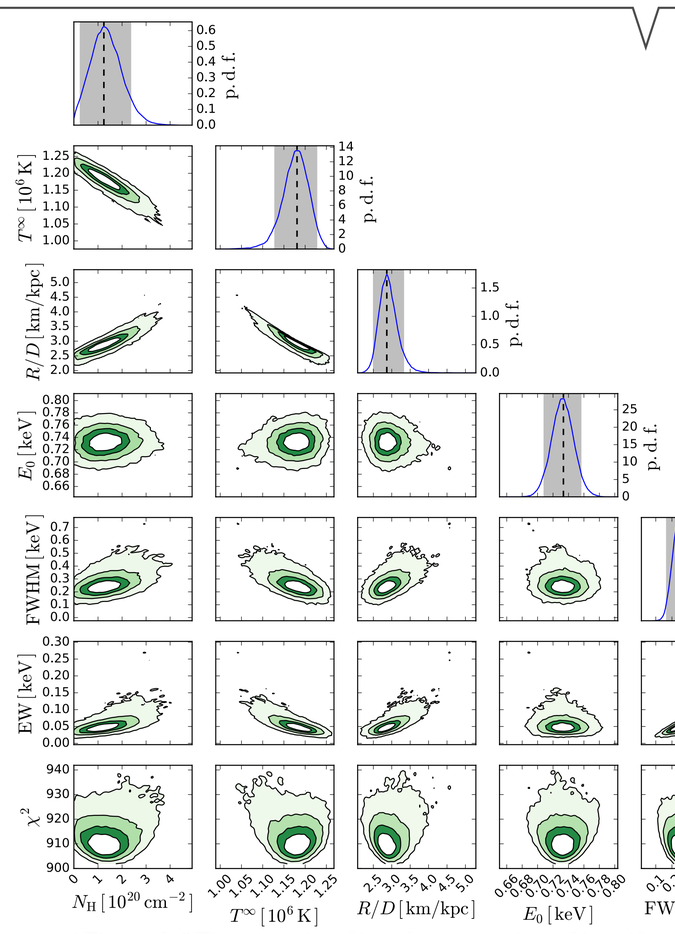
The timing parameters are drastically different from these of NSs of The Magnificent Seven group (*left*; Halpern et al. 2013). This is at odds with the assumption made that Calvera could have been one of The Magnificent Seven (Rutledge et al. 2008). Hasn't been detected neither in gamma-rays (Halpern 2011) nor in radio (Zane et al. 2011). The pulsed fraction is rather high and increases with the photon energy (*middle*; Halpern et al. 2013). The upper limit on the gamma-ray luminosity is orders of a magnitude below gamma-ray luminosities of pulsars with similar E-dot (*right*; Halpern et al. 2013), which is the most puzzling thing about Calvera. The Calvera's proper motion of 69 mas/yr detected recently (Halpern & Gotthelf 2015) is not very large and, before that, it was proposed that Calvera might be a descendant from a runaway star (Posselt et. al 2008).

Optical observations



The vicinity of the Calvera X-ray position as seen in the optical g' and i' bands with the GTC. Ellipses show 90% uncertainties for the Calvera X-ray position and optical positions of two nearby sources D and E, revealed by the observations.

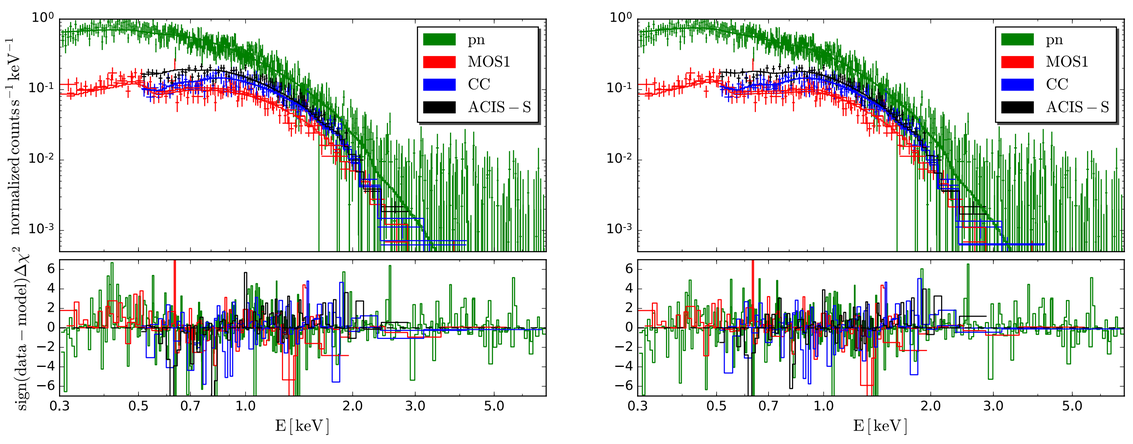
NSMAX1200*GABS model in a spotlight



1D and 2D marginalized posterior distributions for the NSMAX(1200)×GABS model. Gray-filled regions correspond to 90% HPD credible intervals. Contours are for 40%, 68%, 90%, and 99% levels.

$$\chi^2/\text{d.o.f.} = 902/892$$
$$N_{\rm H} = 1.2^{+1.2}_{-0.9} \times 10^{20}\,\text{cm}^{-2}$$
$$T^\infty = 1.18^{+0.05}_{-0.05} \times 10^6\,\text{K}$$
$$R/D = 2.9^{+0.4}_{-0.4}\,\text{km/kpc}$$
The line parameters :
$$E_0 = 0.73^{+0.03}_{-0.03}\,\text{keV}$$
$$\text{FWHM} = 0.24^{+0.10}_{-0.07}\,\text{keV}$$
$$\text{Eq. width} = 0.05^{+0.02}_{-0.02}\,\text{keV}$$

X-ray data



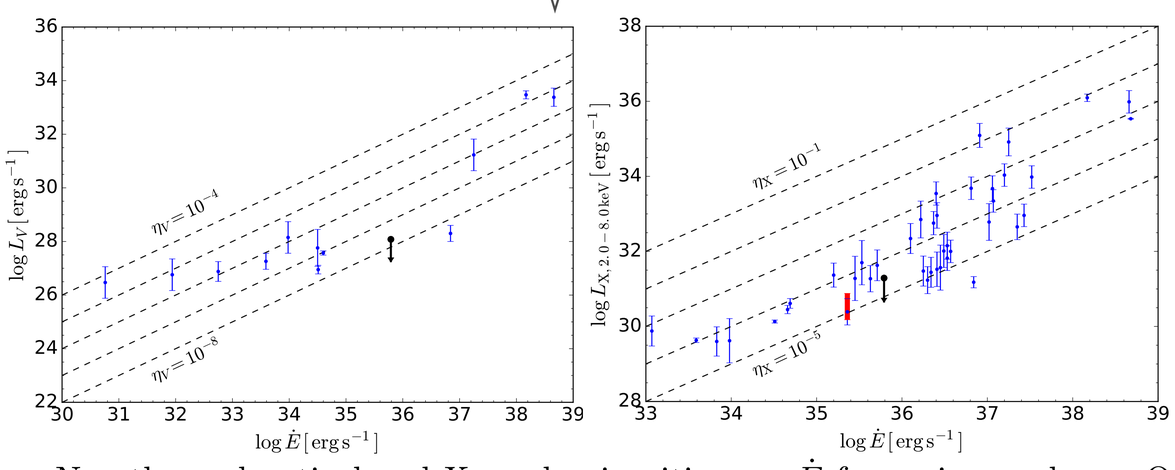
The X-ray spectra of Calvera and the best-fit hydrogen atmosphere model with uniform temperature (NSMAX 1200) without (*left*) and with (*right*) absorption feature.

Table3: Best-fit parameters for NSMAX models.

Model NSMAX	$N_{\rm H}$ [10^{20} cm^{-2}]	T^∞ [10^6 K]	R/D [km/kpc]	E_0 [keV]	FWHM [keV]	EW [keV]	χ^2/d.o.f.
			without absorption line				
123100	< 1.1	$0.84^{+0.03}_{-0.02}$	$5.9^{+0.6}_{-0.6}$	–	–	–	943/895
123190	< 0.3	$1.34^{+0.01}_{-0.02}$	$2.4^{+0.2}_{-0.1}$	–	–	–	977/895
1200	< 0.4	$1.25^{+0.02}_{-0.01}$	$2.4^{+0.1}_{-0.2}$	–	–	–	962/895
			with absorption line				
123100	$2.0^{+0.9}_{-0.9}$	$0.79^{+0.03}_{-0.03}$	$7.4^{+1.1}_{-1.1}$	$0.74^{+0.03}_{-0.03}$	$0.20^{+0.10}_{-0.08}$	$0.03^{+0.02}_{-0.01}$	906/892
123190	< 1.3	$1.29^{+0.03}_{-0.05}$	$2.7^{+0.4}_{-0.2}$	$0.74^{+0.02}_{-0.02}$	$0.25^{+0.07}_{-0.07}$	$0.05^{+0.02}_{-0.02}$	907/892
1200	$1.2^{+1.2}_{-0.9}$	$1.18^{+0.05}_{-0.05}$	$2.9^{+0.4}_{-0.4}$	$0.73^{+0.03}_{-0.03}$	$0.24^{+0.10}_{-0.07}$	$0.05^{+0.02}_{-0.02}$	902/892

Notes. Temperatures T^∞ are given as measured by a distant observer. Ratios R/D are weighted averages of corresponding values for various instruments and their uncertainties therefore account for both statistical and systematic errors. EW is equivalent width. All errors correspond to 90% HPD credible intervals derived via MCMC.

Comparison of Calvera with other pulsars



Non-thermal optical and X-ray luminosities vs. $\dot{E}$ for various pulsars. Optical luminosities are in the V band and X-ray luminosities are in the 2–8 keV range. Calvera upper limits for the distance of 2 kpc are shown by black dots with vertical arrows. Dashed lines in both panels correspond to various efficiencies stepped by order of magnitude.

Conclusions

Puzzling appearance of Cavera can be explained if we assume that it is an ordinar rotation-powered pulsar at a rather large distance of 1.5–5 kpc whose surface is covered with hydrogen atmosphere. In this case, the Calvera's progenitor must be a runaway star.

*Original results presented here are published in Shibanov et al., 2016, ApJ, 831, 112 (http://adsabs.harvard.edu/abs/2016ApJ...831..112S).

If you have any questions and/or suggestions, write to **danila@astro.ioffe.ru.