Pulsar Astrophysics the Next Fifty Years
Proceedings IAU Symposium No. 337, 2017
P. Weltevrede, B.B.P. Perera, L.L. Preston
& S. Sanidas, eds.

doi:10.1017/S1743921317010304

The Puzzling Source at the Center of the SNR RCW 103

A. Borghese[1], **N. Rea**[1,2], **F. Coti Zelati**[2] **and P. Esposito**[1]

[1]Anton Pannekoek Institute for Astronomy,
University of Amsterdam, Amsterdam, the Netherlands
email: `a.borghese@uva.nl`

[2]Institute of Space Sciences (IEEC-CSIC), Campus UAB,
Barcelona, Spain

Abstract. 1E 161348-5055 (1E 1613), the source at the center of the supernova remnant RCW 103, has defied any easy classification since its discovery, owing to its long-term variability (a factor of ~ 100 in flux on time scales from months to years) and a periodicity of 6.67 hr with a variable light curve profile across different flux levels. On June 2016, 1E 1613 emitted a magnetar-like millisecond burst of hard X-rays accompanied with a factor ~ 100 brightening in the persistent soft X-ray emission. The duration and spectral decomposition of the burst, the discovery of a hard X-ray tail in the spectrum, and the long-term outburst history suggest that 1E 1613 is an isolated magnetar and the periodicity of 6.67 hr is the rotational spin period, making 1E 1613 the slowest neutron star ever detected.

Keywords. X-rays: stars, stars: neutron, stars: individual (1E 161348-5055)

1. Introduction

1E 161348-5055, 1E 1613 hereafter, was discovered by the *Einstein* X-ray observatory close to the geometrical center of the young (~ 3 kyr; Carter *et al.* 1997) supernova remnant (SNR) RCW 103. It was classified as the first radio-quiet isolated, cooling neutron star (NS) (Touhy & Garmire 1980). Recent observations have allowed us to gather information about its puzzling nature, highlighting its uniqueness in the NS scenario.

Because of its location at the center of a SNR, its soft thermal X-ray emission and lack of a radio counterpart, 1E 1613 is traditionally labelled as central compact object (CCO). CCOs are young, steady, isolated, X-ray-emitting neutron stars, detected close to the center of SNRs, without emission in other wavelengths and with rotational periods in the range of $0.1 - 0.5$ s. However its timing behaviour makes 1E 1613 stand out among the CCOs. This puzzling object shows a strong variability in flux on a months/year time-scale, experiencing an outburst in 1999 that yielded an increase in flux by a factor of $\sim$ 100. Moreover, a long (~ 90 ks) *XMM–Newton* observation, carried out in 2005, caught the source in a low state and revealed unambiguously a periodicity of 6.67 hr (De Luca *et al.* 2006). In addition to this intriguing phenomenology, the source shows flux variability on short time-scale according to its activity level: in a low state the light curve has a sine-like shape with a clear modulation at 6.67 hr, while in a high state the shape is more complex with numerous dips and peaks (Fig.1). Based on these characteristics two main interpretations were put forward: 1E 1613 could be either the first low-mass X-ray binary in a SNR (in this case the 6.67-hr periodicity would be the orbital period of the system; Bhadkamkar & Ghosh 2009) or a young magnetar with a rotational period of 6.67 hr.

Last year a new event shed light on the peculiar behaviour of this source: a magnetar-like burst was detected by the *Swift* Burst Alert Telescope (BAT) from the direction of the SNR RCW 103 (D'Aì *et al.* 2016, Rea *et al.* 2016). In this proceeding we summarise

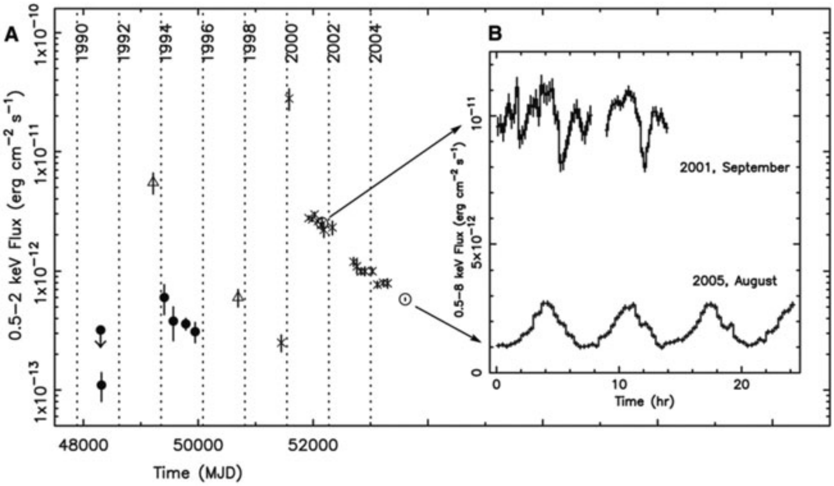

Figure 1. Panel A: 0.5 – 2 keV flux history with measurements by *Rosat* (black filled circles), *ASCA* (triangles), *Chandra* (crosses) and *XMM–Newton* (empty circles). The 1999-2000 outburst is characterized by a two-order of magnitude enhancement of the flux. Panel B: source flux variation over the 2001 (50 ks; upper curve) and 2005 (90 ks; lower curve) *XMM–Newton* observations. Credit: de Luca *et al.* 2006.

the properties of this burst and its implications for the interpretation of the source nature (for further details we refer to Rea *et al.* 2016).

2. Results

Swift BAT triggered on a millisecond burst of hard X-rays from a direction consistent with the position of the point-like X-ray source 1E 1613 in the SNR RCW 103 on 22 June 2016 at 02:03 UT (see Rea *et al.* 2016 for details about the data reduction and analysis). The total duration of the event is ∼ 10 ms and the corresponding light curve shows a double-peak profile (Fig.2, left panel). We fitted the spectra of the two peaks with a blackbody model. The inferred blackbody temperatures are 9.2 ± 0.9 keV and 6.0 ± 0.6 keV for the first ∼ 5 ms of the event and for the second peak, respectively. The total observed flux is $(1.6 \pm 0.2) \times 10^{-6}$ erg cm^{-2} s^{-1} in the 15–150 keV energy range, that corresponds to a luminosity of $\sim 2 \times 10^{39}$ erg s^{-1}(assuming a distance of 3.3 kpc; Caswell *et al.* 1975). Thanks to a *Swift* X-ray Telescope (XRT) monitoring campaign with monthly observations we were able to catch the source in an enhanced X-ray state ∼ 20 minutes before the BAT trigger with an observed flux of $\sim 1.2 \times 10^{-10}$ erg cm^{-2} s^{-1} in the 1–10 keV energy range. The previous XRT observation was performed in May 2016 and the source was still in quiescence.

After the BAT trigger, 1E 1613 was simultaneously observed by *Chandra* for 44.2 ks and *Nuclear Spectroscopic Telescope Array* (*NuSTAR*) for 70.7 ks on 25 June 2016. We detected for the first time a hard component that extends up to ∼ 30 keV. A satisfactory, simultaneous fit of *Chandra* and *NuSTAR* spectra is given by a model that consists of two absorbed ($N_H = 2.05(5) \times 10^{22}$ cm^{-2}) blackbodies with temperatures $kT_1 = 0.52 \pm 0.01$ keV and $kT_2 = 0.93 \pm 0.05$ keV with the inclusion of a power-law component with photon index $\Gamma = 1.20 \pm 0.25$ (Fig.2, middle panel). The total observed 1–10 keV flux is $(3.7 \pm 0.1) \times 10^{-11}$ erg cm^{-2} s^{-1}. For the timing analysis, we performed a blind search for fast (0.01-1000 Hz) periodic and non-periodic signal in both data sets, but we could derive only upper limits (for the corresponding values see Rea *et al.* 2016). The periodicity of 6.67 hr was detected in both observations. The 1–8 keV *Chandra* and 3–79 keV *NuSTAR* light curves were fitted with two sinusoidal harmonics with fundamental

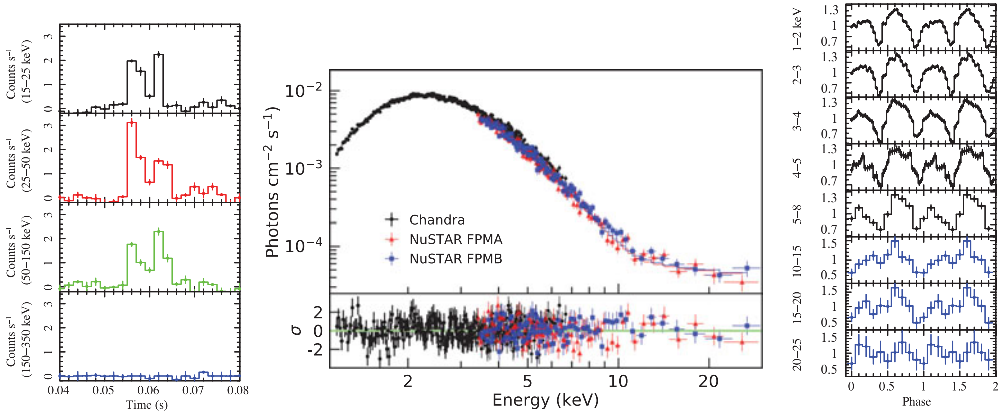

Figure 2. Left panel: *Swift* BAT burst light curves at different energies (bin size: 2 ms). Credit Image: Rea *et al.* 2016. Middle panel: simultaneous fit of the *Chandra* (1–8 keV) and both *NuSTAR* focal plane modules (FPMA and FPMB; 3–30 keV) data with the best-fitting model, consisting of two absorbed blackbodies and a power law. Figure adapted from Rea *et al.* 2016. Right panel: energy-dependent, folded light curves for the simultaneous *Chandra* (1–8 keV) and *NuSTAR* (10–25 keV) observations soon after the burst. Credit image: Rea *et al.* 2016.

periods of 23983 ± 263 s and 24095 ± 164 s, respectively; indeed the corresponding pulse profiles show two peaks per cycle (Fig.2 , right panel). We studied the pulse profile in different energy bands: pulsed emission was detected up to ~ 20 eV and the profile seems to smooth to a single peak as the energy increases. Assuming the ephemeris of Esposito *et al.* (2011) we derive an upper limit for the value of the period derivative of $7 \times 10^{-10}\,\mathrm{s\,s^{-1}}$.

Moreover, we re-analysed all the *Chandra*, *XMM–Newton*, and *Swift* archival observations from 1999 until July 2016 in a consistent way. We fitted all the spectra with a two blackbody model fixing the column density to the value derived from the last *Chandra* pointing (the hard power-law component is not required in the 1–8 keV energy range). Figure 3, right panel, shows the long-term 0.5–10 keV luminosity history: during the past 17 years the source experienced two outbursts. The luminosity decay of the 1999 outburst is fitted by a constant, that represents the quiescent level of $\sim 2.3 \times 10^{33}\,\mathrm{erg\,s^{-1}}$, plus three exponential functions. The total inferred energy is $\sim 9.9 \times 10^{42}$ erg in the 0.5–10 keV band. We have an on-going monitoring *Swift* XRT campaign (last observation performed on 16 October 2017). This campaign allows us to constrain better the decay of the new second outburst, that is modelled by the combination of a constant and two exponential functions (Fig.3, right panel). Including the last observation, we derive a total emitted energy of $\sim 2 \times 10^{42}$ erg in the 0.5–10 keV band.

3. Discussion

The millisecond burst and its spectrum, the X-ray outburst energetics and the spectral decomposition, the variability of the modulation in time and energy are all properties consistent with 1E 1613 being a magnetar. In coincidence with the second outburst, a non-thermal component was detected up to ~ 30 keV for the first time. Hard X-ray emission has been detected in at least half of the magnetar population (Olausen & Kaspi 2014); it could be either steady or transient linked to the outburst peak. Outbursts are believed to be driven by magnetic instabilities of twisted bundles that stress the crust (Beloborodov 2009). The twisted bundles have a high electron density, therefore the seed thermal photons get scattered by resonant Compton scattering, creating non-thermal high-energy components in the spectrum. If the electron density decreases when the bun-

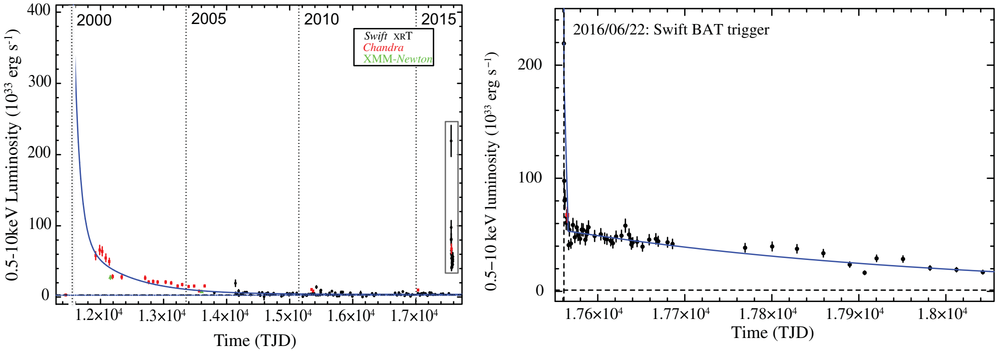

Figure 3. Left panel: long-term 0.5–10 keV luminosity history between September 1999 and July 2016 as observed by *Chandra*, *XMM–Newton* and *Swift*. Dashed line is the source quiescent luminosity. Right panel: long-term 0.5–10 keV luminosity history observed by *Swift* XRT since the onset of the second outburst. Last observation was performed on 16 October 2017.

dles untwist, the hard X-ray tail gets dimmer until undetectability once the source reaches again the quiescence. In this scenario the hard X-ray emission is transient. If the magnetar has stable twists, the non-thermal emission is expected in outburst and quiescence, being thus persistent. A new *NuSTAR* observation performed on June 2017 confirms the transient behaviour of the hard power-law component (Borghese *et al.* in prep.).

If 1E 1613 is a magnetar, it should be an extremely slow magnetar with a rotational period of 6.67 hr, that represents the longest spin period ever detected for an isolated NS. The slowest magnetar observed so far has a period of ~ 12 s. Given the strong evidence for the magnetar interpretation of this source, an efficient braking mechanism has to be invoked to slow down 1E 1613 to a period of 6.67 hr in ~ 3 kyr. The classical magneto-dipolar braking would require a huge magnetic field of the order of $\sim 10^{18}$ G, therefore an external torque is needed. The most likely scenario involves a propeller interaction with a fall-back disk. 1E 1613 seems to be a magnetar that experienced a strong supernova fall-back accretion episode in the past (Chevalier 1999). If it was born with a field and a spin period such that when the accretion begins, the source is in the propeller regime, the fall-back materials do not reach the source and exert a spin-down torque on the NS. Many efforts have been made also by other collaborations to explain such a long period. For instance, Ho & Andersson (2017) predict a remnant disk with a mass of $\sim 10^{-9}$ $M_\odot$ around a millisecond NS that initially is in an ejector phase (necessary for the dynamo generation of magnetar-strength magnetic fields), and after hundreds of years its rotation is slow enough to allow the onset of a propeller phase (during which strong torques cause an increase of the spin period).

References

Beloborodov, A. M. 2009, *ApJ*, 703, 1044
Bhadkamkar, H. & Ghosh, P. 2009, *A&A*, 506, 1297
Carter, L. M., Dickel, J. R., & Bomans D. J. 1997, *PASP*, 109, 990
Caswell, J. L., Murray, J. D., Roger, R. S. *et al.* 1975, *A&A*, 45, 239
Chevalier, R. A. 1999, *ApJ*, 511, 798
D'Aì, A., Evans, P., Burrows, D. N. *et al.* 2016, *MNRAS*, 463, 2394
De Luca, A., Caraveo, P. A., Mereghetti S. *et al.* 2006, *Science*, 313, 814
Esposito, P., Turolla, R., De Luca A. *et al.* 2011, *MNRAS*, 418, 170
Ho, W. C. G. & Andersson, N. 2017, *MNRAS*, 464, L65
Olausen, S. A. & Kaspi, V. M. 2014, *ApJS*, 212, 6
Rea, N., Borghese, A., Esposito, P. *et al.* 2016, *ApJ*, 828, L13
Tuohy, I. & Garmire, G. 1980, *ApJ*, 239, L107