Swift monitoring of the central X-ray source in RCW 103

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ABSTRACT

The X-ray source 1E 161348−5055 lies at the centre of the 2-kyr-old supernova remnant RCW 103. Owing to its 24-ks modulation, orders-of-magnitude flux variability over a few months/years and lack of an obvious optical counterpart, 1E 161348−5055 defies assignment to any known class of X-ray sources. Starting from 2006 April, Swift observed 1E 161348−5055 with its X-Ray Telescope for ∼2 ks approximately once per month. During the five years covered, the source has remained in a quiescent state, with an average observed flux of ∼1.7×10^{-12} erg cm^{-2} s^{-1} (1–10 keV), ∼20 times lower than the historical maximum attained in its 1999–2000 outburst. The long time-span of the Swift data allows us to obtain an accurate measure of the period of 1E 161348−5055 [P = 24 030.42(2) s] and to derive the first upper limit on its period derivative (∣\dot{P}∣ < 1.6×10^{-9} s^{-1} at 3σ).

Key words: stars: neutron – pulsars: general – X-rays: individual: 1E 161348−5055.

1 INTRODUCTION

1E 161348−5055 (hereafter 1E 1613) was discovered with the Einstein satellite (Tuohy & Garmire 1980) close to the geometrical centre of the young supernova remnant (SNR) RCW 103 (age ∼2 kyr; Carter, Dickel & Bomans 1997). It was proposed as the first example of a radio-quiet (possibly owing to an unfavourable radio beaming), isolated, cooling neutron star (Tuohy & Garmire 1980; Tuohy et al. 1983; Gotthelf, Petre & Hwang 1997).

At present, there is little doubt that 1E 1613 is indeed a neutron star (De Luca et al. 2006) and the source is traditionally included in the class of the ‘central compact objects’ (CCOs; see De Luca 2008, for a review). CCOs are a small group of young and seemingly isolated X-ray-emitting neutron stars (with thermal-like spectra), observed close to the centre of non-plerionic SNRs and without obvious counterparts in other wavebands. However, its peculiar temporal behaviour distinguishes 1E 1613 from the other CCOs (actually, it singles this source out as a unique object in general). The first peculiarity of the source is its orders-of-magnitude X-ray flux variability on a few months/years time-scale (Gotthelf, Petre & Vasisht 1999; Garmire et al. 2000a; Becker & Aschenbach 2002; Sanwal et al. 2002). Moreover, the first Chandra observation of 1E 1613 in a low state hinted at a possible periodicity at ∼6 h (Garmire et al. 2000b) that was not confirmed by subsequent observations of the source in bright states. A long (90 ks) observation with XMM–Newton, performed in 2005, caught 1E 1613 in a low state and yielded unambiguous evidence for a strong, nearly sinusoidal modulation at 6.67 ± 0.03 h (24.0 ± 0.1 ks; De Luca et al. 2006). The same periodicity was then recognized also in the older data sets, albeit with a very different pulse shape, including two narrow dips per period. No faster pulsations are seen in 1E 1613 (De Luca et al. 2006).

Large flux variations, similar to those observed in 1E 1613, are common among magnetars (e.g. Rea & Esposito 2011), but these pulsars, whose emission is believed to be powered mainly by the magnetic field, are characterized by rotational periods in the narrow range 2–12 s. On the other hand, CCOs are steady sources, and their periods – when known – are in the 0.1–0.5 s range (Zavlin et al. 2000; Gotthelf, Halpern & Seward 2005; Gotthelf & Halpern 2009). If 1E 1613 is indeed a magnetar, it must have been slowed down by some unusual mechanisms, perhaps by a propeller interaction with a debris disc (De Luca et al. 2006; Li 2007). A different possibility is that 1E 1613 is a peculiar low-mass binary,1 powered by a double

1Deep observations of the field of 1E 1613 with the Very Large Telescope and the Hubble Space Telescope showed only two or three faint infrared sources (H ∼ 22) consistent with the position of 1E 1613. If none of them is linked to the X-ray source, 1E 1613 is undetected in the near-infrared down to H > 23 (De Luca et al. 2008).

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(wind plus disc) accretion on to a recently born compact object (in this case the 24-ks signal would result from the orbital motion of the system) or hosting a magnetar (De Luca et al. 2006; Pizzolato et al. 2008; Bhadkamkar & Ghosh 2009). Both scenarios require non-standard assumptions about the formation and evolution of compact objects in supernova explosions.

Here we report on the results from a 5-year monitoring of 1E 1613 with the Swift satellite (Gehrels et al. 2004). This unique data set allowed us to obtain a phase-coherent timing solution encompassing also Chandra and XMM–Newton archival observations. Thanks to this, we are able to derive an accurate period for 1E 1613 and to set the first upper limits on the period derivative for this puzzling source.

2 X-RAY OBSERVATIONS AND DATA REDUCTION

2.1 Swift data

The X-Ray Telescope (XRT; Burrows et al. 2005) on-board Swift uses a front-illuminated CCD detector sensitive to photons between 0.2 and 10 keV with an effective area of about 110 cm$^2$ (at 1.5 keV) and a field of view of 23 arcmin in diameter. Two main readout modes are available: photon counting (PC) and windowed timing (WT). PC mode provides two-dimensional imaging information and a 2.5073-s time resolution; in WT mode only one-dimensional imaging is preserved, achieving a time resolution of 1.766 ms.

Between 2006 April and 2011 April, 1E 1613 was observed by XRT 49 times, for a total net exposure time of 102.8 ks in PC mode. The distribution of the Swift observations can be seen in the long-term light curve in Fig. 1, while in Fig. 2 we show the image of 1E 1613 and RCW 103 resulting from all the XRT data gathered so far. Except for periods in which the source was not visible by the XRT because of pointing constraints of the Swift spacecraft, approximately one 2-ks observation in imaging mode was collected per month. On a few occasions, when 1E 1613 showed hints of consistent flux variations, we requested target-of-opportunity observations. For example, this happened at the end of 2010 October (see Fig. 1 around MJD 55500), when the source count rate remained at a relatively high level of $\approx 0.09$ count s$^{-1}$ for a few consecutive pointings spanning $\sim 5$ d. The observations were not time-constrained, so the monitoring can be considered a casual sampling of the phase of 1E 1613.

2 Also 5.5 ks of WT data were collected during the same pointings. However, given the bright SNR in which 1E 1613 is embedded (see Fig. 2), we did not make use of them in this work.

2.2 Chandra and XMM–Newton data

We complemented the Swift/XRT data set with the few Chandra and XMM–Newton observations long enough to contain a minimum of two modulation cycles of 1E 1613 (Table 1). The Chandra/ACIS-S observation (performed on 2002 March 03, when the source was rather bright) has been already published in Sanwal et al. (2002); the XMM–Newton/EPIC (2005 August 23–24) and Chandra/HRC-S (2007 July 03) ones, both carried out while 1E 1613 was in a low state, have been published in De Luca et al. (2006) and De Luca et al. (2008), respectively; we refer to these papers for more details. The Chandra/ACIS-I observation of 2010 June 01 is reported here

Table 1. XMM–Newton and Chandra observations used for this work.

| Instrument        | Obs.ID  | Date$^a$ (MJD TDB) | Duration$^b$ (ks) |
|-------------------|---------|--------------------|-------------------|
| Chandra/ACIS-S    | 2759    | 52336.489          | 50.3              |
| XMM–Newton/EPIC   | 0302390101 | 53605.824    | 87.5              |
| Chandra/HRC-S     | 7619    | 54284.330          | 80.2              |
| Chandra/ACIS-I    | 11823   | 55348.604          | 62.5              |

$^a$Mid-point of observation.
$^b$Time between the first and the last events.
for the first time. For this work the data were processed and analysed with standard procedures, using the latest available versions of the Chandra Interactive Analysis of Observation software (CIAO, version 4.2) and of the XMM–Newton Science Analysis Software (SAS, version 10).

3 ANALYSIS AND RESULTS

We merged the data from the Swift/XRT observations and accumulated a combined spectrum (a detailed spectral analysis will be reported elsewhere). The data were rebinned with a minimum of 20 counts per energy bin and the background was estimated from an annular region centred on 1E 1613 (with radii 10 and 20 pixel, see Fig. 2). The spectrum can be fitted [$\chi^2 = 0.82$ for 174 degrees of freedom (d.o.f.)] by a double-blackbody corrected for the interstellar absorption (see De Luca et al. 2006). The best-fitting parameters are blackbody temperatures $kT_1 = 0.50^{+0.06}_{-0.08}$ keV and $kT_2 = 0.8^{+0.5}_{-0.1}$ keV, radii $R_1 = 0.6^{+0.2}_{-0.1}$ km and $R_2 = 0.12^{+0.06}_{-0.09}$ km (for a distance of 3.3 kpc; Caswell et al. 1975), and absorption $N_H = (7.4^{+0.2}_{-0.3}) \times 10^{21}$ cm$^{-2}$ (1σ errors). The observed averaged flux is $\sim 1.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, similar to that measured with XMM–Newton in 2005 August (De Luca et al. 2006).

As can be seen from Fig. 1, 1E 1613 showed only moderate variability between the many Swift pointings, remaining always well below the flux level of the 1999–2000 outburst ($\sim 5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$; Garmire et al. 2000a). Also the Chandra HRC-S and ACIS-I observations show a flux of $\sim 2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. We note that on a statistical ground we are sensitive only to outbursts lasting $\geq 1$ month. Although shorter phases of enhanced emission cannot be ruled out for 1E 1613 based on our data, the historical behaviour of the source indicates that its outbursts are likely longer than a few months (De Luca et al. 2006). Thus, our data suggest that 1E 1613 persisted in a quiescent state during the five years of the Swift monitoring.

Owing to their long time-span (from MJD 53804.500 to 55632.581), the Swift data are suitable for studying the 24-ks modulation of 1E 1613. A folded profile showing a significant modulation cannot be obtained from the XRT data using the most accurate period available so far, i.e. the one estimated from the 2005 August XMM–Newton observation ($P = 24.0 \pm 0.1$ ks; De Luca et al. 2006). This is not surprising since $\sim 200$ d separate the XMM–Newton observation from the start of the Swift monitoring, and the XMM–Newton period uncertainty implies a phase uncertainty of half a cycle after only $\sim 30$ d.

So, as a starting point, we computed a fast Fourier transform power spectrum using all the Swift data at the highest resolution allowed by the PC mode (bin time 2.5073 s). Given the approximate knowledge of the source period, a ‘blind’ search is not, in principle, necessary, but we did this to have a clear picture of the Swift time series: considerable noise can be expected to result from both source flux variations and the Swift uneven sampling of the light curve, and a search restricted around the XMM–Newton period would have involved the risk of selecting a spurious signal, in the case the true signal was embedded in a high level of non-white noise. As expected, significant noise is present, but a very prominent peak at 24.031(2) s (the quoted uncertainty indicates the Fourier period resolution) stands out well above the noise level, with a Leahy-normalized power (Leahy et al. 1983) of 425 (Fig. 3). While the non-white noise does not affect the frequency of a real signal, it alters the statistical properties of a time series; following the recipes of Israel & Stella (1996) we estimate that, after taking into account the number of frequencies searched, the probability of having a signal this strong by chance coincidence is lower than $3 \times 10^{-9}$ (that is a detection at a higher than 5.9σ confidence level). Moreover, the signal is consistent with the periodicity measured by XMM–Newton. We also note that no other periodicity with significance higher than 3σ was found up to $\sim 1$ yr.

We folded the Swift data, as well as those of the observations in Table 1, on the period $P = 24.031$ s. We obtained very significant pulse profiles; those of the data taken during the quiescent state of 1E 1613 (Swift, XMM–Newton, Chandra/HRC-S and ACIS-I) are single-peaked (and well modelled by two or three sine functions with the periods fixed at the fundamental period and higher harmonics, with phases and amplitudes free to vary), while that from the Chandra/ACIS-S observation shows two asymmetric peaks per cycle, both exhibiting two subpeaks. In order to obtain a refined ephemeris, we studied the phase evolution through the epoch-folded data by means of an iterative phase-fitting technique (see e.g. Dall’Osso et al. 2003). Given the variability of the pulse shape, we did not make use of a pulse template to cross-correlate with, but we inferred the phase of the modulation by fitting each individual folded profile with the fundamental plus three higher harmonics.

As a first step, we fit the phases of the fundamental harmonic obtained from the Swift data divided into four segments of approximately equal length and from the XMM–Newton and Chandra HRC-S and ACIS-I observations. At this stage, the Chandra/ACIS-S observation was left out, because of its very different pulse profile. The time evolution of the phase can be followed unambiguously throughout all the data and described with a linear relation of the form $\phi = \phi_0 + 2\pi(t - t_0)/P$. We assumed the start of the Swift monitoring, MJD 55804.0, as the reference epoch $t_0$ and the fit ($\chi^2 = 0.88$ for 5 d.o.f.) gives $P_X = 24.030(42.2)$ s (1σ uncertainty, valid over the range MJD 53605–55632). We designate this rotational ephemeris ‘solution A’. A quadratic term $-\pi(t - t_0)^2 P / P^2$, which would reflect the presence of a periodic derivative ($P'$), is not required. This implies an upper limit on the period derivative of 1E 1613 of $|P_A| < 3.3 \times 10^{-9}$ s$^{-1}$ (3σ confidence level). In Fig. 4 we show the epoch-folded pulse profiles (including the Chandra/ACIS-S one) obtained using this solution. We note that the XMM–Newton observation was affected by rather intense proton flares. The removal of the intervals of flaring background, because of the few cycles contained in the observation, significantly affects the pulse profiles. As a check of the robustness of our results, we repeated the timing

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Footnote:

3This is the minimum number of harmonics necessary to properly fit all the folded profiles, including the multipeaked Chandra/ACIS-S one. The timing analysis described in the following was performed also with a slightly different approach: the phases of the individual folded profiles were derived by a fit with a variable number of harmonics, determined on a case-by-case basis by requesting that the addition of a further (higher) harmonic is not statistically significant (by means of a Fisher test) with respect to the null hypothesis; the results are essentially identical.
Figure 4. 32-bin epoch-folded pulse profiles of 1E 1613 obtained from different instruments (as indicated in each panel). The blue line distinguishes the Chandra/ACIS-S data, which were used in deriving solution B but not for solution A (see Section 3 for details). In red we overplotted the XMM–Newton/EPIC data before the filtering for proton flares. The fundamental harmonic of the pulse profile is shown in green in each panel (in the EPIC panel it refers to the filtered data). (See the online version of this paper for the colour figure.)

analysis using the unfiltered EPIC data and we obtained virtually identical results (both filtered and unfiltered profiles are plotted in Fig. 4).

Using solution A, we are able to predict for 1E 1613 the phase of the fundamental harmonic at the epoch of the Chandra/ACIS-S observation within ±0.03 cycles (at 3σ). The phase of the fundamental harmonic measured in the Chandra/ACIS-S data nicely dovetails with the predicted value. Thus, we derived a new coherent timing solution, which we denote with ‘B’, including the Chandra/ACIS-S data and therefore valid over the range MJD 52336–55632. Again, the phases of the fundamental harmonic can be fitted with a linear relation ($\chi^2 = 0.77$ for 6 d.o.f.) which yields $P_B = 24030.42(2)$ s (1σ uncertainty; epoch MJD 55804.0). While the best-fitting period is equal to that of solution A, the limit on the period derivative is slightly more constraining: $|\dot{P}_B| < 1.6 \times 10^{-9}$ s$^{-1}$ (3σ confidence level).

4 DISCUSSION

We presented the analysis of the first five years (2006 April–2011 April) of the Swift/XRT monitoring of the enigmatic X-ray source 1E 1613 at the centre of the SNR RCW 103. During this time-span, the source remained in a quiescent state, with an average observed 1–10 keV flux of $\sim 1.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, 20–30 times lower than the historical maximum attained in the 1999–2000 outburst ($\sim 5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$; Garmire et al. 2000a). The timing study of the Swift data yielded an accurate measure of the modulation period of 1E 1613 which allowed us to phase-connect the XRT data with archival Chandra and XMM–Newton observations. We derived two timing solutions, labelled A and B, both consistent with the same constant period $P_A = P_B = 24030.42(2)$ s but with somewhat different upper limits on the period derivative. Solution A ($|\dot{P}_A| < 3.3 \times 10^{-9}$ s$^{-1}$; MJD 53605–55632) is based on the single-peaked pulse profiles observed while 1E 1613 was in quiescence. Solution B ($|\dot{P}_B| < 1.6 \times 10^{-9}$ s$^{-1}$; MJD 52336–55632) is a natural extension of solution A including the multipeaked Chandra/ACIS-S profile obtained on 2002 March 03, when 1E 1613 was in a rather bright state (Sanwal et al. 2002).

The phase-coherent timing technique employed in our timing study of 1E 1613 closely parallels the well-tested (virtually all systems are under control) procedures used for X-ray bright spin-powered pulsars. For such objects it is implicitly assumed that the pulse profile does not intrinsically change in time, so that, when a Fourier decomposition of the pulse is introduced, neither the fundamental nor the higher harmonics evolve. In such a picture all the variability is due to Poisson noise and the phase evolution can be tracked by matching the pulse profile at any given epoch always with the same template.

In the case of 1E 1613 there are clear indications that the pulse shape changes in time so that the previous assumptions are not valid. This forced us to abandon the standard template-matching analysis and follow instead the phase of the fundamental (first) harmonic. The main justification for such an approach is that usually (moderate) pulse shape changes are associated with higher harmonics, while the fundamental is stable. Even if this seems to be the case for 1E 1613, given the stability of the phase of the fundamental harmonic over several years, we stress that it does not have to hold in general (see e.g. Hartman et al. 2008).

In the following we discuss the implications of our newly derived upper limit $|\dot{P}| < 1.6 \times 10^{-9}$ s$^{-1}$ on the models that have been proposed so far for 1E 1613. We remark that all the ensuing considerations are based on the assumption (discussed above) that the fundamental harmonic is a good tracer of the timing behaviour of the source.

Although the nature of 1E 1613 is still an open issue, most interpretations favour the neutron star scenario, in which the star is either isolated (De Luca et al. 2006; Li 2007) or in a binary system with a low-mass companion (Pizzolato et al. 2008; Bhadkamkar & Ghosh 2009). While the model by Bhadkamkar & Ghosh (2009) is

4The large phase uncertainties do not allow a similar study of the higher harmonics (which are not even always detectable).
based on a fast-spinning, moderately magnetized neutron star in a 6.67-h eccentric orbit, in all the other cases an ultramagnetized neutron star ($B \approx 10^{15}$ G) is required to explain the very long period of 1E 1613 and the observed X-ray periodicity is related to the star spin period [in the binary scenario of Pizzolato et al. (2008) the latter may or may not coincide with the orbital period]. Actually, as already noted by De Luca et al. (2006), magnetodipolar braking alone is not enough to explain the present value of $P$ even invoking a magnetar, and spin-down by the interaction of the star magnetosphere with a (residual) disc is also necessary for an isolated object. Spin-down to $P \approx 6.67$ h in a time $\sim 2$ kyr can be achieved if the initial period is peculiarly long [$\gtrsim 300$ ms (De Luca et al. 2006); magnetars are in fact believed to be born with ms periods (Thompson & Duncan 1993)]. Using different assumptions on the termination radius of the disc (see Ekşi & Alpar 2005), Li (2007) showed that the same result can be recovered also for more conventional values of the initial period ($\approx 10$ ms).

The current spin-down rate expected in the binary magnetar model is very small since the equilibrium period is reached well in advance of $\sim 1000$ yr, unless the synchronization time is very short ($\sim 10$ yr) and there is no mass transfer in the system (Pizzolato et al. 2008). If 1E 1613 is an object of this kind, our upper limit on $P$ is completely non-constraining for the model.

On the other hand, if 1E 1613 is an isolated magnetar surrounded by a fossil disc, it must be a quite rare system. According to the Monte Carlo simulations of Li (2007), the fraction of objects of this type with periods $\gtrsim 100$ s at an age of 2.5 kyr is only $\sim 1$ per cent. The large majority of stars are much faster rotators ($P \sim 1–10$ s) in the ejector stage (typically identified with SGRs/AXPs), while ultraslow systems are in the propeller/accretor phase.\(^5\)

The spin-down rate of a neutron star which interacts with a fossil disc in the propeller stage is given by $\dot{P} \sim -M R_\text{in}^2 \Omega_\text{K}(R_\text{in}) - 2\pi P^2/(\pi I)$, where $\dot{R}_\text{in} = 0.5B^4 R_\text{in}^3/(864GM^3)$ is the Alfvén radius, $M \sim 1.4M_\odot$ and $R \sim 10^8$ cm are the star mass and radius ($I \sim 10^{45}$ g cm$^2$ is the moment of inertia); $B$ is the surface magnetic field, $\Omega_\text{K}$ is the Keplerian angular velocity and $M \propto t^{-1/3}$ is the mass-loss rate from the disc (Li 2007, and references therein).\(^5\) If 1E 1613 is currently in the propeller phase, $\dot{P}$ can be derived from the previous expressions with $P \sim 24$ ks and $t \sim 2.5$ kyr, as a function of the disc initial mass $M_{\text{disc}}(0)$ and of $B$. Results are shown in Fig. 5 (lower panel) for $10^{-6} < M_{\text{disc}}(0)/M_\odot < 10^{-2}$ and $3.2 \times 10^{13} < B < 10^{16}$ G; the Alfvén radius as a function of $M_{\text{disc}}(0)$ and $B$ is plotted in the upper panel. Comparison of $R_{\text{in}}$ with the light cylinder radius, $R_{\text{LC}} = cP/(2\pi)$, and the corotation radius, $R_\text{c} = \sqrt{GM/P^2/(4\pi^2)}$, shows that the star is currently in the propeller phase, characterized by $R_\text{c} < R_{\text{in}} < R_{\text{LC}}$, only if $B \gtrsim 10^{15}$ G. Lower values of the field or large enough (depending on $B$) initial disc mass would result in 1E 1613 being in the accretor stage. The resulting values of $P$ are orders of magnitude above the upper limit we reported [as a reference, the case discussed in De Luca et al. (2006) has $P \sim 10^{-7}$ s$^{-1}$], with the only exception of an extremely narrow range of $M_{\text{disc}}(0)$ for each $B$. Although not all the values of $M_{\text{disc}}(0)$ and $B$ we considered will produce the correct period at an age of 2.5 kyr (this depends also on both the initial

\(^5\) Although previous figures are model-dependent, the conclusion that propellers/accretors are a tiny minority appears to be robust.

\(^6\) We remark that no complete theory of the interaction of a disc with a magnetized neutron star exists. Following Li (2007), we adopted the ‘efficient’ form of the propeller torque (see e.g. Franci schelli & Wijers 2002, for a comparison of different expressions of the torques).

![Figure 5](https://example.com/figure5.png)
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