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Letter to the Editor

A new symbiotic low mass X-ray binary system: 4U 1954+319

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ABSTRACT

Aims. 4U 1954+319 was discovered 25 years ago, but only recently has a clear picture of its nature begun to emerge. We present for the first time a broad-band spectrum of the source and a detailed timing study using more than one year of monitoring data.
Methods. The timing and spectral analysis was done using publicly available *Swift*, *INTEGRAL*, *Beppo*SAX, and *RXTE*/ASM data in the 0.7 to 150 keV energy band.
Results. The source spectrum is described well by a highly absorbed ($N_{\rm H} \sim 10^{23}$ cm^{-2}) power law with a high-energy exponential cutoff around 15 keV. An additional black body component is needed below 3 keV to account for a soft excess. The derived ~5 h periodicity, with a spin-up timescale of ~25 years, could be identified as the neutron star spin period. The spectral and timing characteristics indicate that we are dealing both with the slowest established wind-accreting X-ray pulsar and with the second confirmed member of the emerging class dubbed "symbiotic low mass X-ray binaries" to host a neutron star.

Key words. binaries: close – pulsars: individual: 4U 1954+319 – stars: neutron – X-rays: binaries

1. Introduction

Since its discovery by the *ARIEL* satellite in 1981, 4U 1954+319 has appeared as a flaring X-ray source (Warwick et al. 1981). Located in the Cygnus region, this source was observed by different X-ray telescopes (Forman et al. 1978; Cook et al. 1984; Warwick et al. 1988; Tweedy et al. 1989; Voges et al. 1999). From the observed spectral behaviour, the source was tentatively classified as a high-mass X-ray binary system hosting a neutron star (NS). However, little was known about the system, as the optical counterpart was not identified due to the ambiguous determination of the source position. The companion star was then classified as a close M-type giant or a distant and reddened Be star (Cook et al. 1984; Tweedy et al. 1989).

Recently, using the *Chandra* refined source position, Masetti et al. (2006) used optical spectroscopy to identify its companion as an M 4–5 III star, which is located within 1.7 kpc. Such identification suggests the system is composed of a compact object accreting through the wind of its M-type giant companion star. This makes 4U 1954+319 the third low mass X-ray binary (LMXB) hosting an NS and a late type giant companion, after GX 1+4 (e.g. Chakrabarty & Roche 1997) and possibly 4U 1700+24 (Gaudenzi & Polcaro 1999), for which however no coherent pulsation has been reported to date (e.g. Masetti et al. 2002). Therefore 4U 1954+319 could be attributed to the so-called "symbiotic X-ray binaries", an emerging subclass of LMXBs. These systems with an evolved giant donor are the probable progenitors of most wide-orbit LMXBs (Chakrabarty & Roche 1997).

Only recently has a periodic signal been reported from this source, whit a period of ~5.09 h quasi-monotonically decreasing (Corbet et al. 2006). If this period can be attributed to the spin, 4U 1954+319 would be the slowest binary NS known, with the possible exception of the enigmatic source 1E 161348-5055 in the Supernova remnant RCW 103 (De Luca et al. 2006). In this Letter we used several high-energy observations to unveil the nature of 4U 1954+319 through spectroscopic and timing analysis.

2. Observations and data analysis

The *INTEGRAL* data set was obtained using the 2003/2005 publicly available observations within <12° from the source direction. We analysed 613 pointings from the IBIS/ISGRI coded mask telescope (Ubertini et al. 2003; Lebrun et al. 2003) at energies between 18 and 200 keV, for a total exposure time of 1.4 Ms. The data reduction was performed using the standard Offline Science Analysis (OSA) version 5.1. We extracted the 20–60 keV band light curve based on the single pointings. During the *INTEGRAL* observation, 4U 1954+319 was mainly in a quiescent phase (52 717–53 144 MJD), and in the last part of the observation, it entered a strong outburst phase (53 312–53 708 MJD) with an increase in count rate of a factor 40. During the outburst phase, 4U 1954+319 is clearly detected in the mosaic image with a significance level of ~45σ. During the quiescent phase, 4U 1954+319 was not detected at a statistically significant level in the ISGRI data. Therefore we excluded these data from the timing and spectral analyses.

We also included for the spectral analysis the publicly available data from the Narrow Field Instruments (NFIs) on board *Beppo*SAX. The source 4U 1954+319 was observed on May 4, 1998 for a net exposure of 19 ks in the LECS (Parmar et al. 1997) and for 46 ks in the MECS (Boella et al. 1997).

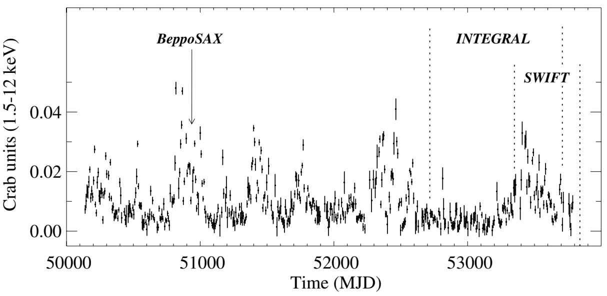

Fig. 1. The 4U 1954+319 *RXTE*/ASM light curve in the 1.5–12 keV energy band (data-averaged over a 7-day interval). We converted the ASM count rate to flux using 1 Crab ≈ 75 cts/s (Levine et al. 1996).

The average spectrum of the source was extracted from a region of 6′ in both instruments. The spectra were then rebinned in order to have at least 30 counts per channel and three channels per resolution element. Note that *Beppo*SAX observations were too short to enable the timing analysis.

We also analysed the *Swift*/BAT (Barthelmy et al. 2005) survey data, collected between December 2004 and April 2006. The analysis was performed using the HEASoft software (release v.6.0.5). For each single pointing (with typical integration time of 5 min), we extracted an image in the 15−50 keV energy range and evaluated the source count rate at the *Chandra* position. Thus, we obtained a barycentered light curve containing ~23 000 data points.

In Fig. 1 we show the *Rossi X-ray Timing Explorer* (*RXTE*) All-Sky Monitor (ASM) light curve of 4U 1954+319, where we report the time interval in which the *INTEGRAL*, *Swift*, and *Beppo*SAX observations were performed.

2.1. Spectral analysis

For the spectral analysis, we used ISGRI (18−150 keV), LECS (0.7–4.5 keV), and MECS (1.7−10 keV) data. The non-imaging *Beppo*SAX spectrometer PDS data (15−300 keV) could not be used due to the contamination of Cyg X−1. The analysis was done using XSPEC version 11.3 (Arnaud 1996). All spectral uncertainties in the results are given at a 90% confidence level for single parameters.

We first computed a hardness-intensity diagram using the *RXTE*/ASM data. The hardness is the ratio of the count rates in the 1.5−5 keV to the ones in the 5−12 keV energy band, and the intensity is the 1.5−12 keV count rate. Each point corresponds to ~7 days of integration time. The source shows a significant linear correlation (slope ≈ 1) between flux and hardness. Therefore we searched for spectral changes in the ISGRI data, dividing the observation into four different intensity levels. We fitted each subset with a simple power-law (PL) model, but it turned out to be statistically inadequate (χ^2/d.o.f. = 43/12). The best fit was found by replacing the PL with a cutoff PL model thereby obtaining a χ^2/d.o.f. = 10/11. We found the spectral parameters for the four data sets to be the same within the error bars, most likely due to the low statistics during the flare, so we did not observe the same hardness-intensity correlation as observed below 12 keV with the ASM data. The best-fit values for the average ISGRI spectrum are found for a PL photon index, Γ, of 0.7 ± 0.1 and a high-energy cutoff $E_{\rm c} \sim 14^{+9}_{-3}$ keV.

We then fitted the *Beppo*SAX spectrum using a simple photoelectrically-absorbed PL model plus a black body (BB) model for the soft excess below 3 keV, as often observed in accreting pulsars (e.g. Hickox et al. 2004) and a Gaussian emission line, resulting in a χ^2/d.o.f. = 132/71. The best fit was found for a heavily absorbed spectrum with $N_{\rm H} = 2.8 \pm 0.2 \times 10^{23}$ cm^{-2}, a BB temperature of $kT = 0.11 \pm 0.01$ keV to model the soft X-ray excess, a PL index of $\Gamma = 1.5 \pm 0.5$, $E_{\rm c} \sim 17 \pm 12$ keV, and an iron emission line at ~6.33 ± 0.15 keV (with the line width fixed at 0.5 keV). The quite high reduced χ^2 indicates that the soft excess is not perfectly modeled by the BB component. The hydrogen column density, $N_{\rm H}$, is found to be 30 times higher than the Galactic value reported in the radio maps of Dickey & Lockman (1990).

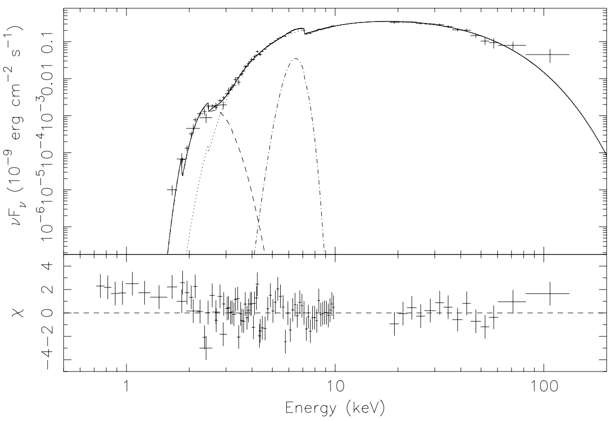

Fig. 2. Broad-band spectrum of 4U 1954+319, fitted with an absorbed BB, Gaussian line, and cutoff PL. The data points correspond to the LECS/MECS (0.7–10 keV) and ISGRI (18−150 keV) spectra. The lower panel shows the residuals with respect to the best-fit model.

The cutoff value is not well-constrained using the NFIs or ISGRI alone. This is due to the fact that it falls outside of the energy ranges of the individual instruments. In order to better constrain the broad-band (0.6−200 keV) spectral characteristics we jointly fitted the NFI and the ISGRI data. A multiplicative factor for each instrument was included in the fit to account for the uncertainty in the cross-calibration of the instruments, as well as variability across the non-simultaneous observations. The best-fit parameters are $\Gamma = 1.1 \pm 0.1$, $E_{\rm c} = 17 \pm 2$ keV, $kT = 0.123 \pm 0.004$ keV, and a similar value of $N_{\rm H}$, with a χ^2/d.o.f. of 138/83. The broad-band spectrum, together with the best-fit model, are shown in Fig. 2.

2.2. Timing analysis

For the timing analysis we used the BAT (15−50 keV) and ISGRI (18−50 keV) light curves after solar-system barycentric correction.

We searched for coherent pulsations of the source in the BAT data by computing a power density spectrum (PDS) in the frequency range between 2×10^{-8} and 10^{-4} Hz from fast Fourier transforms. In the resulting PDS, a signal is evident at $\nu = 5.45 \times 10^{-5}$ Hz. The peak is broad with an *FWHM* of 6.7×10^{-7} Hz, suggesting a period evolution. Therefore the light curves were grouped into 100 cycles per time interval, and the best period was determined using an epoch-folding analysis. The distribution of the χ^2 values versus trial period were fitted as described in Leahy (1987). The resulting 14 best-period values clearly show a spin-up trend, see Fig. 3.

Using the ISGRI light curves, we confirmed the presence of a period at ~5.17 h. We attempted to search for a period change in the ISGRI data; but due to the sparse coverage using the 100 cycle time intervals, we could only derive 2 significant

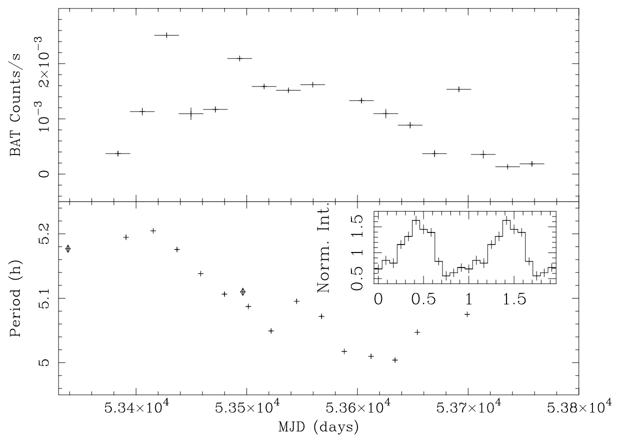

Fig. 3. *Upper panel*: BAT light curve (15–50 keV) of 4U 1954+319. The time bin size is 22 days. *Lower panel*: period evolution as measured with BAT (crosses) and ISGRI (diamonds). The inset represents the normalized BAT phase folded light curve between 53 400 and 53 500 MJD considering P and $\dot{P}$. Two cycles are shown for clarity.

measurements (see Fig. 3), which are consistent with the previous findings.

Fitting the period evolution with a linear function, the derived spin-up trend is around -3×10^{-5} s s^{-1}, which implies a spin-up time scale ($P/\dot{P}$) of ~25 years. However, we note that some scattering around this trend is present, indicating a possible local spin-down. On the other hand, a much better fit was obtained using a sinusoidal function, indicating a possible orbital period of 385 ± 4 days and a projected semimajor axis, $a_x \sin i$, of 178 ± 4 AU. However, since this periodicity is of the order of the time interval spanned by the data, it is difficult to identify it with a possible orbital period (see below).

3. Discussion

The timing and broad-band spectrum of 4U 1954+319 allowed us to investigate for the first time the nature of this system, which only recently has been tentatively attributed to the emerging NS "symbiotic LMXBs" class.

The ~5 h measured periodicity could be due either to the system orbital modulation or to the rotation of the compact object. We can rule out that we are measuring the system orbital period. In fact, given the typical luminosity and temperature of an M 4–5 III star (Lang 1992), the stellar evolutionary models with solar metallicities (Claret 2004) predict a mass of ~1.2 $M_\odot$ for the companion. Assuming a mass within 3 $M_\odot$ for the compact object, the orbital separation would be much smaller than the donor star radius (~80 $R_\odot$). We are then left with the hypothesis of measuring the spin period of the NS hosted in the system (a white dwarf would be excluded due to the excessive torque required, as already noted by Corbet et al. 2006).

Furthermore, the observed spin-up could be attributed to the accretion torque on the magnetized NS. While suggestive of a sinusoidal trend (see Fig. 3 and Sect. 2.2), the time evolution of the period cannot be accounted for by the Doppler shift of the system's orbital motion: in this case the derived orbital parameters would imply a companion star mass of a few 10^6 $M_\odot$. Thus we can consider ~400 days a lower limit to the orbital period of the system. This implies a wide orbit ($a > 2\times10^{13}$ cm) and explains the fact that the optical spectrum reported by Masetti et al. (2006) shows no sign of the influence of the X-ray source.

We found a broad-band spectrum typical of accreting X-ray pulsars (e.g. Joss & Rappaport 1984) and, in particular, similar to the ones of GX 1+4 (Paul et al. 2005), and 4U 1700+24 (Tiengo et al. 2005). The high column density found of the order of 3×10^{23} cm^{-2} could be attributed to the local (circumstellar) absorption. In fact, this value is typical of the local environment of symbiotic stars as indicated by observations of Rayleigh scattering in their UV spectra (Schmid 1997). The measured luminosity of $\sim2\times10^{35}$ erg s^{-1}, assuming a 1.7 kpc source distance, points towards a wind-fed accretion system with the companion not filling its Roche lobe. Taking the period, its derivative, and the luminosity into account, one can use the standard accretion torque models (Henrics 1983; Joss & Rappaport 1984) to derive an order-of-magnitude value for the dipolar magnetic field of the NS. It turns out to be $B \sim 10^{12}$ G, which implies a magnetospheric radius $r_\mathrm{m} = 3\times10^8$ cm $(L_\mathrm{X}/10^{37}\,\mathrm{erg\,s^{-1}})^{-2/7}\,(B/10^{12}\,\mathrm{G})^{4/7} \sim 10^9$ cm, smaller than the corotation radius ($r_\mathrm{co} = (GM_\mathrm{X}P^2_\mathrm{spin}/4\pi^2)^{1/3} \sim 1.2\times10^{11}$ cm, where $M_\mathrm{X} \sim 1.4$ $M_\odot$ is the mass of the NS), allowing the accretion process. We are hence dealing with a regular wind accreting X-ray pulsar but with the longest known spin period.

The very long period measured in 4U 1954+319 can be explained by taking into account the age of the companion star ($\sim9\times10^9$ yr, Claret 2004) and the standard binary pulsar evolutionary picture (Davies & Pringle 1981). In fact, a newborn NS experiences a spin-down initially due to the magnetic dipole braking (radio phase). In our case this phase lasts $\sim8\times10^9$ yr, namely the time the donor spends on the main sequence. Since the orbit is quite wide, the NS can spin down practically as if it was isolated. When the donor star leaves the main sequence, starting to evolve rapidly into a red giant, the star mass loss increases and there is coupling between the infalling matter stopped by the magnetosphere and the magnetosphere itself (propeller phase, Illarionov & Sunyaev 1975). By means of these processes during its whole lifetime, an NS with a magnetic field of a few 10^{12} G can reach periods of the order of 10^4 s in $\sim8.5\times10^9$ yr.

The distance where the ram pressure of the accretion flow balances the magnetic pressure is called the Alfvén radius. A further increase in the accretion rate, as the donor becomes a red giant, allows the corotation radius to overcome the Alfvén radius and the NS to start accreting, becoming observable in X-rays and spinning-up. The emerging picture is an old, hence slow, NS accreting from the slow and dense wind of an evolved M type giant on a wide orbit. The inhomogeneities of the wind can explain the observed long-term X-ray variability (see Fig. 1). The wide orbit also allowed the companion star not to be affected by the Supernova explosion that generated the NS thereby enabling the donor star to follow its natural evolutionary track.

4. Conclusions

We analysed most of the recently available high-energy data of 4U 1954+319, deriving for the first time its broad-band (0.7–150 keV) spectrum and analysing its timing characteristics. The luminosity and spin period derivative of the system allowed us to infer a pulsar magnetic field of the order of 10^{12} G. In the framework of standard binary pulsar evolutionary models, this value, coupled to the age of the companion star, can justify the very long observed NS period without invoking any additional spin-down process.

It turns out that 4U 1954+319 is the slowest accretion powered NS, and it is hosted in a "symbiotic LMXB" system. These are rare systems that could eventually evolve into wide-orbit binary systems hosting an NS and a white dwarf, but without mass transfer so hence very difficult to observe.

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References

Arnaud, K. A. 1996, in Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby, & J. Barnes (San Francisco: ASP), ASP Conf. Ser., 101, 17

Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, Space Sci. Rev., 120, 143

Boella, G., Chiappetti, L., Conti, G., et al. 1997, A&AS, 122, 327

Chakrabarty, D., & Roche, P. 1997, ApJ, 489, 252

Claret, A. 2004, A&A, 424, 919

Cook, M. C., Warwick, R. S., & Watson, M. G. 1984, in X-ray Astronomy 1984, ed. M. Oda, & R. Giacconi (Komaba: Institute of Space and Astronautical Science), 225

Corbet, R., Barbier, L., Barthelmy, S., et al. 2006, Astron. Telegram, 797

Davies, R. E., & Pringle, J. E. 1981, MNRAS, 196, 209

De Luca, A., Caraveo, P. A., Mereghetti, S., et al. 2006, Science, 313, 814

Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215

Forman, W., Jones, C., Cominsky, L., et al. 1978, ApJS, 38, 357

Gaudenzi, S., & Polcaro, V. F. 1999, A&A, 347, 473

Henrics, H. F. 1983, in Accretion-Driven Stellar X-ray Sources, ed. W. H. G. Lewin, & E. P. J. van den Heuvel (Cambridge and New York: Cambridge University Press), 393

Hickox, R. C., Narayan, R., & Kallman, T. R. 2004, ApJ, 614, 881

Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185

Joss, P. C., & Rappaport, S. A. 1984, ARA&A, 22, 537

Lang, K. R. 1992, Astrophysical Data: Planets and Stars (New York: Springer-Verlag)

Lebrun, F., Leray, J.-P., Lavocate, Ph., et al. 2003, A&A, 411, L141

Leahy, D. A. 1987, A&A, 180, 275

Levine, A. M., Bradt, H., & Cui, W. 1996, ApJ, 469, L33

Li, X.-D., & van den Heuvel, P. J. 1999, ApJ, 513, L48

Masetti, N., Dal Fiume, D., Cusumano, G., et al. 2002, A&A, 382, 104

Masetti, N., Orlandini, M., Palazzi, E., et al. 2006, A&A, 453, 295

Parmar, A. N., Martin, D. D. E., Bavdaz, M., et al. 1997, A&AS, 122, 309

Paul, B., Dotani, T., Nagase, F., Mukherjee, U., & Naik, S. 2005, ApJ, 627, 915

Schmid, H. M., 1997, in Physical Processes in Symbiotic Binaries, ed. J. Mikołajewska, Copernicus Foundation for Polish Astronomy, Warsaw, 21

Tiengo, A., Galloway, D. K., Di Salvo, T., et al. 2005, A&A, 441, 283

Tweedy, R. W., Warwick, R. S., & Remillard, R. 1989, in Two Topics in X-Ray Astronomy, Vol. 1: X-Ray Binaries, ed. J. Hunt, & B. Battrick, ESA SP-296, 661

Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A, 411, L131

Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389

Warwick, R. S., Brinkman, N, Fraser, G. W., et al. 1981, MNRAS, 270, 711

Warwick, R. S., Norton, A. J., Turner, M. G., et al. 1988, MNRAS, 232, 551