Publication Year	2016
Acceptance in OA@INAF	2020-04-29T09:33:09Z
Title	EXTraS discovery of an 1.2-s X-ray pulsar in M 31
Authors	Esposito, P.; ISRAEL, Gian Luca; Belfiore, A.; Novara, G.; SIDOLI, Lara; et al.
DOI	10.1093/mnrasl/slv194
Handle	http://hdl.handle.net/20.500.12386/24301
Journal	MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY. LETTERS
Number	457

Mon. Not. R. Astron. Soc. **000**, 1–5 (2015) Printed 3 December 2015 (MN LaTeX style file v2.2)

EXTraS discovery of an 1.2-s X-ray pulsar in M 31

P. Esposito,[1⋆] G. L. Israel,[2] A. Belfiore,[1] G. Novara,[3] L. Sidoli,[1] G. A. Rodríguez Castillo,[2] A. De Luca,[1] A. Tiengo,[1,3,4] F. Haberl,[5] R. Salvaterra,[1] A. M. Read,[6] D. Salvetti,[1] S. Sandrelli,[7] M. Marelli,[1] J. Wilms[8] and D. D'Agostino[9]

[1] *INAF–Istituto di Astrofisica Spaziale e Fisica Cosmica - Milano, via E. Bassini 15, I-20133 Milano, Italy*
[2] *INAF–Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*
[3] *IUSS–Istituto Universitario di Studi Superiori, piazza della Vittoria 15, I-27100 Pavia, Italy*
[4] *INFN–Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, via A. Bassi 6, I-27100 Pavia, Italy*
[5] *Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, D-85748 Garching, Germany*
[6] *Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, U.K.*
[7] *INAF–Osservatorio Astronomico di Brera, via Brera 28, I-20121 Milano, Italy*
[8] *ECAP–Erlangen Centre for Astroparticle Physics, Sternwartstrasse 7, D-96049 Bamberg, Germany*
[9] *CNR–Istituto di Matematica Applicata e Tecnologie Informatiche, via de Marini 6, I-16149 Genova, Italy*

Accepted 2015 December 1. Received 2015 November 25; in original form 2015 November 13

ABSTRACT

During a search for coherent signals in the X-ray archival data of *XMM–Newton*, we discovered a modulation at 1.2 s in 3XMM J004301.4+413017 (3X J0043), a source lying in the direction of an external arm of M 31. This short period indicates a neutron star (NS). Between 2000 and 2013, the position of 3X J0043 was imaged by public *XMM–Newton* observations 35 times. The analysis of these data allowed us to detect an orbital modulation at 1.27 d and study the long-term properties of the source. The emission of the pulsar was rather hard (most spectra are described by a power law with $\Gamma < 1$) and, assuming the distance to M 31, the 0.3–10 keV luminosity was variable, from $\sim 3 \times 10^{37}$ to 2×10^{38} erg s^{-1}. The analysis of optical data shows that, while 3X J0043 is likely associated to a globular cluster in M 31, a counterpart with $V \gtrsim 22$ outside the cluster cannot be excluded. Considering our findings, there are two main viable scenarios for 3X J0043: a peculiar low-mass X-ray binary, similar to 4U 1822–37 or 4U 1626–67, or an intermediate-mass X-ray binary resembling Her X-1. Regardless of the exact nature of the system, 3X J0043 is the first accreting NS in M 31 in which the spin period has been detected.

Key words: galaxies: individual: M 31 – X-rays: binaries – X-rays: individual: 3XMM J004301.4+413017

1 INTRODUCTION

EXTraS (Exploring the X-ray Transient and variable Sky) is a project to explore systematically the serendipitous content of the *XMM–Newton* European Photon Imaging Camera (EPIC) pn (Strüder et al. 2001) and MOS (Turner et al. 2001) data in the temporal domain. The results will be released to the astronomical community in an easy-to-use form. The project includes a search for fast transients missed by standard image analysis, as well as the search and characterisation of variability (both periodical and aperiodical) in hundreds of thousands of sources, spanning more than nine orders of magnitude in time scale (from <1 s to >10 yr) and six orders of magnitude in flux (from 10^{-9} to 10^{-15} erg cm^{-2} s^{-1}in 0.2–12 keV). See De Luca et al. (2015) or the project web site, www.extras-fp7.eu, for details.

At the moment of writing, about 7,400 *XMM–Newton* observations were retrieved and around 1.1 million time series from sources detected with the EPIC CCDs in imaging mode were searched for periodic signals in a systematic and automatised way with the detection algorithm described in Israel & Stella (1996). Among dozens of new X-ray pulsators found so far with periodic signals at high confidence ($>4.5\sigma$), there is 3XMM J004301.4+413017 (3X J0043) in M 31. 3X J0043 (Supper et al. 2001; Kaaret 2002) lies in the direction of an external arm to the north-east of the galaxy, and was proposed as a high-mass X-ray binary (HMXB) by Shaw Greening et al. (2009). The suggestion was based on its hard X-ray spectrum and the coincidence (within 0.7 arcsec) with a $V = 17.2$ object found in the optical catalogue by Massey et al. (2006). However, based on the proximity of the source to the M 31 globular cluster GlC 377 (Kaaret 2002; Trudolyubov & Priedhorsky 2004; Pietsch, Freyberg, & Haberl 2005), Stiele et al. (2011) observed a low-mass X-ray binary (LMXB) in

---

⋆ E-mail: paoloesp@iasf-milano.inaf.it

Table 1. Logbook of the *XMM–Newton* observations used in this work. The full table is available online (see Supporting Information).

Obs. ID	Start date	Exposure^a (ks)		Off-axis^b (arcmin)	Count rate^c (10^{-2} s^{-1})
0112570601	28-12-2000	13.3	(8.8)	15.8	1.97 ± 0.17
0112570101	06-01-2002	64.3	(48.3)	15.9	2.58 ± 0.08
0402560901	26-12-2006	61.9	(38.3)	14.7	3.39 ± 0.10
0405320701	31-12-2006	15.9	(12.2)	15.5	3.47 ± 0.19
0405320801	16-01-2007	13.9	(10.5)	15.5	3.76 ± 0.21

[a] In parentheses we give the good observing time after dead-time correction and screening for soft proton flares.

[b] Radial off-axis angle of 3X J0043 from the boresight of the pn telescope.

[c] Net source count rate in the 0.3–10 keV energy band using the extraction regions described in the text; the values are not corrected for point spread function and vignetting effects.

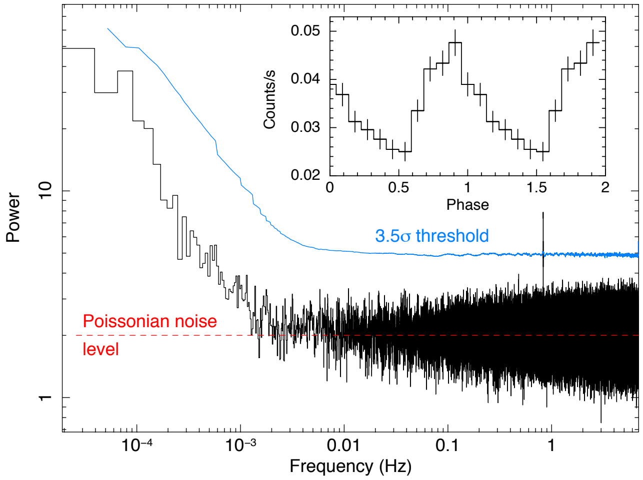

Figure 1. Fourier power spectrum from the December 2000–February 2013 pn data (0.5–10 keV; average of 36 Fourier transforms; $\Delta t \simeq 73$ ms, 262,144 frequencies). The blue line corresponds to the 3.5σ confidence level threshold for potential signals and was computed taking into account the number of trials, equal to the number of frequency bins of the spectrum. The prominent peak above the threshold corresponds to the 1.2-s signal. The inset shows the light curve of the data set 0650560301 (where the signal was discovered) folded to its best period.

hard state would be more likely.

Here we report on the discovery in 3X J0043 of a period of 1.2 s and an orbital modulation at 1.27 d. These findings clearly indicate a neutron star (NS) in a binary system. This is the first NS in M 31 for which a spin period has been detected. Using all the public *XMM–Newton* observations (Sect. 2), as well as optical data (Sect. 3), we discuss the nature of this new X-ray pulsar (Sect. 4).

2 *XMM–Newton* OBSERVATIONS AND ANALYSIS

The region of 3X J0043 was repeatedly observed with *XMM–Newton* with the EPIC detectors in full imaging mode (Full Frame). The source was always off-axis, at an angle varying from ∼2 to 16 arcmin, but by about 15 arcmin in most observations. Since the time resolution of the MOS cameras (2.6 s) is not adequate to sample the 1.2-s pulsation and in most pointings the source fell out of the field of view of the MOSs, we used only the pn data (readout time: 73 ms). The public pn data sets covering the position of 3X J0043 (apart from a few in which the source was located in a CCD gap and no useful data were collected) are summarised in Table 1. They span from December 2000 to February 2013.

The raw observation data files (ODF) retrieved from the *XMM–Newton* Science Archive were processed with the Science Analysis Software (SAS) v.14. The screening of time periods with high particle background was based on the good-time intervals included in the processed pipeline products (PPS). We extracted the event lists and spectra using an extraction radius of 20 arcsec, and estimated the background from regions near the source, with radius of 25 arcsec and avoiding CCD gaps. To convert the event times to the barycentre of the Solar System, we processed the event files with the SAS task BARYCEN using the source position. Spectra were rebinned so as to obtain a minimum of 30 counts per energy bin, and for each spectrum we generated the response matrix and the ancillary file using the SAS tasks RMFGEN and ARFGEN.

2.1 Discovery of the period and timing analysis

A periodic signal at about 1.2 s was first detected at a confidence level of about 6.5σ by the automatic analysis in the pn data of obs. 0650560301 (see Table 1). By a Z_1^2 (or Rayleigh test), the value was refined to 1.203830 ± 0.000003 s; the corresponding pulse profile is single-peaked, with a substantial pulsed fraction [$(50 \pm 2\%)$, root mean square (RMS)]. Subsequently, we computed a power spectrum using the whole available data set (for a timespan of about 12 years) and this confirmed the presence of the 1.2-s signal at a confidence greater than 12σ (Fig. 1).

In each observation, we measured the period by the Z_1^2 test. A constant fit shows that the periods are not consistent with a single value, with a reduced χ^2 (χ^2_ν) higher than 200 for 33 degrees of freedom (dof). The inclusion of a period derivative component (or of higher-order derivatives) does not give better fits. On the other hand, the inspection of the longest observations reveals a strong modulation of the pulsar period, which is consistent with Doppler shifts induced by an orbital motion with period of ≈1 d.

To model the binary parameters, we began by dividing the data into ∼30-ks-long segments. We searched each segment for coherent pulsations around the spin period, through a polynomial fit with PRESTO (Ransom 2001). We could collect good quality time of arrival of the pulses (TOAs) with a cadence of 1.5–3 ks. Obs. 0690600401 (see Table 1) covers a full orbit and we could infer a preliminary binary solution, by fitting the orbital parameters together with the spin period with TEMPO2 (Hobbs et al. 2006) using the binary model ELL1 (Lange et al. 2001). We extended the timing solution to obs. 0112570101, taken more than 10 years before, slightly refining the orbital period estimate, and fitting for the spin period at the epoch of the observation. Because this estimate of the orbital period suffers from aliasing, we broke this degeneracy by analysing in the same way also obs. 0650560301. The orbital solution, reported in Table 2, produces residuals of 80–100 ms (RMS) in each observation. The spin periods measured at the 3 epochs are 1.203892 ± 0.000001 s on MJD 52281, 1.203644 ± 0.000003 s on MJD 55566, and 1.2037007 ± 0.0000003 s on MJD 56105, indicating alternated trends of spin-up and -down. A detailed timing analysis of 3X J0043 will be addressed in a dedicated forthcoming publication. We finally notice that no significant flux variations are observed along the orbit, with a 3σ upper limit on the modulation amplitude set from obs. 0690600401 at 10%.

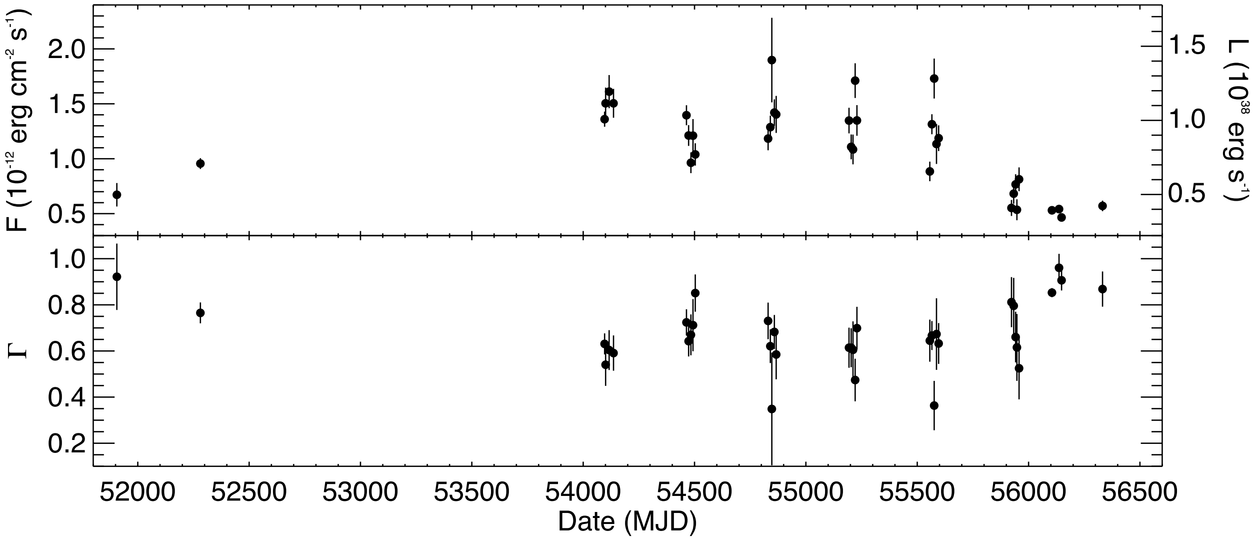

Figure 2. Long-term properties of 3X J0043 as observed with *XMM–Newton*. The flux (upper panel) and the photon index (lower panel) were derived in the 0.3–10 keV range from the power-law fit of all data sets with the $N_{\rm H}$ fixed at the value towards M 31 using the CFLUX model in XSPEC. In the upper panel, the right axis indicates the isotropic 0.3–10 keV luminosity assuming a distance of 780 kpc; to convert from observed flux to (unabsorbed) luminosity, we used a single conversion factor, which is precise to within 2% for each observation.

Table 2. Orbital parameters of 3X J0043.

Parameter	Value
Orbital period, $P_{\rm b}$ (d)	$1.27397828 \pm 0.00000071$
Epoch of ascending node, $T_{\rm asc}$ (MJD)	56104.7912 ± 0.0011
Projected semi-axis, $A_{\rm X} \sin i$ (lt-s)	2.884 ± 0.017
Eccentricity, e	0.011 ± 0.009^{a}
Longitude of periastron, ω (°)	276 ± 41
Mass function ($M_{\odot}$)	0.0159 ± 0.0008
Minimum companion mass[b] ($M_{\odot}$)	0.36

[a] Upper limit at the 3σ confidence level: $e < 0.037$.

[b] Value computed for an orbit viewed edge-on, $i = 90°$.

2.2 Spectral analysis and long-term variability

The spectral fitting was performed in 0.3–10 keV using XSPEC v.12.8; the abundances used are those of Wilms, Allen, & McCray (2000). Using *XMM–Newton* data, Trudolyubov & Priedhorsky (2004) observed that the spectrum of 3X J0043 could be described by a hard power law modified for the interstellar absorption with an equivalent hydrogen column depth $N_{\rm H} = 7 \times 10^{20}$ cm^{-2}, which is the typical value in the direction of M 31.

The power-law model indeed works for most spectra, but when applied to data sets 0690600401 and 0700380601, it overpredicts the emission above 7–8 keV, resulting in poor fits ($\chi^2_\nu = 1.30$ for 157 dof and 1.34 for 32 dof, respectively). It should be noticed that these are the only observations with both small off-axis angle and good count-statistics (Table 1). In particular, the spectrum from obs. 0690600401, which is the richest one, with about 4,500 net counts, is better described by a power-law with an exponential cutoff, or with the addition of a thermal component. Adopting a cutoff power law ($\chi^2_\nu = 1.05$ for 155 dof), the photon index is $\Gamma = 0.0 \pm 0.1$ and the cutoff is located at $3.6^{+0.4}_{-0.3}$ keV; the absorption is poorly constrained, with a 3σ upper limit $N_{\rm H} < 7 \times 10^{20}$ cm^{-2}, and the observed flux is $(4.8 \pm 0.2) \times 10^{-13}$ erg cm^{-2} s^{-1}. For the distance to M 31 (d = 780 kpc; Holland 1998), this translates into a luminosity of $(3.6 \pm 0.1) \times 10^{37}$ erg s^{-1}. A power law plus blackbody model yields a $\chi^2_\nu = 1.09$ for 154 dof, and the parameters are: $N_{\rm H} = (7 \pm 2) \times 10^{20}$ cm^{-2}, $\Gamma = 1.0^{+0.2}_{-0.1}$, $kT = 1.3^{+0.2}_{-0.1}$ keV and a blackbody radius $R_{\rm BB} = 6.5^{+0.9}_{-0.7}$ km (at 780 kpc); the observed flux is $(4.8 \pm 0.2) \times 10^{-13}$ erg cm^{-2} s^{-1} (~40% of which from the blackbody component) and the luminosity is $(3.7 \pm 0.1) \times 10^{37}$ erg s^{-1}. Similar results are obtained for obs. 0700380601.

The automatic analysis of long-term variability performed within the EXTraS project (assuming a constant spectral shape) shows significant changes in flux ($\chi^2_\nu > 80$ for 34 dof for a constant fit), with a factor >2 drop in flux in approximately a year, starting around January/February 2011. We assessed by a 'runs' (Wald–Wolfowitz) test that these changes are not consistent with an unchanging underlying distribution.

We further investigated long-term variability by performing a more detailed spectral analysis. 3X J0043 displays significant spectral variations over the 2000–2013 period. In a simultaneous fit of all spectra with an absorbed power-law model, the variability cannot be accounted for by leaving free to vary in each data set only one of the parameters: either the absorption, the photon index, or the normalisation. Data are well fit by a power-law model with the $N_{\rm H}$ fixed at the M 31 value, when photon indices and normalisations are free to vary ($\chi^2_\nu = 1.16$ for 670 dof; excluding obs. 0690600401 and 0700380601, the fit is even better, with $\chi^2_\nu = 1.03$ for 478 dof). The long-term light curve from the fluxes derived with this simple model is plotted in Fig. 2. The minimum observed flux, on 8 August 2012, was $(4.7 \pm 0.3) \times 10^{-13}$ erg cm^{-2} s^{-1} in the 0.3–10 keV energy band (luminosity: $\sim 3.5 \times 10^{37}$ erg s^{-1}), while the maximum was $(1.9 \pm 0.4) \times 10^{-12}$ erg cm^{-2} s^{-1} (luminosity: 1.5×10^{38} erg s^{-1}) on 15 January 2009. The analysis also confirms the hard spectrum, with photon indices in the range from ~0.35 to 1 (average value: $\Gamma = 0.7$) and shows a hint of a 'harder-when-brighter' correlation between flux and spectral shape. When the absorption is left free to vary but held to a common value for all data sets, the best-fitting value is $(7.5 \pm 0.9) \times 10^{20}$ cm^{-2} ($\chi^2_\nu = 1.16$ for 669 dof).

3 THE OPTICAL FIELD OF 3X J0043

The position of 3X J0043 from the third *XMM–Newton* Serendipitous Source Catalogue (3XMM; Rosen et al. 2015) is $\mathrm{RA}_{\mathrm{J2000}} = 00^{\mathrm{h}}43^{\mathrm{m}}01\overset{\mathrm{s}}{.}48$, $\mathrm{Decl.}_{\mathrm{J2000}} = +41^{\circ}30'16\overset{''}{.}9$ (error radius: about 1.5 arcsec; consistent coordinates and similar uncertainties are given by the *Chandra* Source Catalog; Evans et al. 2010). We inspected a Digitized Sky Survey image of the field of 3X J0043. A very bright source, TYC 2805-2136-1 ($V \sim 11$), is at ~9.5 arcsec (using the Tycho-2 catalogue position; Høg et al. 2000) from 3X J0043. On 20 September 2015, we obtained three spectra of this star using the 1.52-m Cassini telescope at the Loiano Observatory (Italy) equipped with the Bologna Faint Object Spectrograph & Camera (BFOSC). The spectra show no emission lines and allowed us to classify the object as a K0V–K1V spectral-type star. Its large distance from 3X J0043 (also taking into account the proper motion) rules out an association between the two objects.

The position of 3X J0043 was imaged on 19 February 2005 (proposal ID: 10273) by the *Hubble Space Telescope* (*HST*) with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS) instrument using the F555W filter (exposure time of 151 s; dataset J92GA7VLQ), as well as the F814W filter (exposure time of 457 s; dataset J92GA7VMQ). We retrieved geometrically corrected images produced by the on-the-fly reprocessing pipeline from the Mikulski Archive for Space Telescopes (MAST), and we performed a source detection using the SExtractor package (Bertin & Arnouts 1996). For the detection of a source, we required a minimum of five contiguous pixels with a threshold of 5σ above the RMS background, with a total of 32 deblending subthresholds, and with a contrast parameter of 0.0001, setting the background mesh size to 8×8 ACS pixels. Using such approach, the globular cluster GlC 377 (0.6 arcsec from 3X J0043) is undoubtedly identified amid a rather crowded field. No useful photometry could be extracted within ~0.9 arcsec of the globular cluster core, due to source confusion. Outside that region, many sources consistent with the X-ray position of 3X J0043 are detected, the brightest of which have a magnitude of 21.6 ± 0.1 in the F814W filter and of 22.1 ± 0.1 in the F555W filter (ST magnitude system).

We did not identify any star-like source possibly corresponding to the object in the catalogue by Massey et al. (2006), J004301.51+413017.5, with $V = 17.242$, $B–V = -0.655$, $U–B = 1.302$, and $V–R = 0.370$. In the eventuality of an optical transient, we inspected the Kitt Peak National Observatory images used by Massey et al. (2006). We conclude that the source J004301.51+413017.5 was actually a blend of the globular cluster and other sources not resolved in the data of that survey.

4 DISCUSSION

We discovered in 3X J0043 pulsations at 1.2 s, pointing to a NS, and an orbital modulation with period 1.27 d. The X-ray emission was described well enough by a hard power-law with $\Gamma < 1$. On time-scales of years, the X-ray flux varied by a factor ≈5, in the range $\sim 0.5–2 \times 10^{-12}$ erg cm^{-2} s^{-1}. Eclipses or dips were not detected in the light curves, and no modulation of the flux was seen along the orbit, down to a limit of ~10%. This suggests an inclination angle $i \lesssim 60^{\circ}$.

A chance alignment of 3X J0043 with M 31 cannot be ruled out but seems extremely unlikely. The absence of any bright optical counterpart in the deep *HST* images and the high Galactic latitude, $b = -21^{\circ}$, far off the plane, strongly disfavour a Galactic interpretation. Furthermore, the value of the absorbing column of 3X J0043 is very similar to the total Galactic depth in its direction. Several pieces of information also argue against a non-accreting NS, chiefly: the periods of spin-up and -down and the substantial timing noise, the variability of the X-ray emission (or the unusual spectrum in the case of a magnetar), and the high luminosity of $\sim 0.4– 2 \times 10^{38}$ erg s^{-1} (at the distance of M 31 and assuming isotropy). Therefore, we will discuss the nature of 3X J0043 in the hypothesis of an accretion-powered source belonging to M 31.

3X J0043 lies very close to the globular cluster GlC 377 but, considering the crowded field and the positional uncertainties, we think that the association should not be taken for granted. Apart from the unresolved core of the globular cluster, the brightest source detected in the X-ray error circle has a V magnitude of 22.1. We take this value as the limit on the magnitude of the counterpart to 3X J0043. The reddening toward M 31 ($A_V \simeq 0.2$) and its distance module (24.45) implies an absolute visual magnitude, M_V, of the optical counterpart fainter than -2.5. The lower limit on the mass of the companion from the orbital parameters is ~ 0.4 M$_{\odot}$.

If we consider the Corbet diagram of spin versus orbital periods of accreting XRBs (Enoto et al. 2014), there are essentially three possibilities among known objects for an XRB with a spin period of ~1.2 s in a ~1 d orbital period: (i) a HMXB with a Roche-lobe-filling high-mass star; (ii) a peculiar LMXB (similar to 4U 1626–67 and 4U 1822–37); (iii) an 'intermediate-mass' XRB (like Her X–1).

A HMXB (i) is highly unlikely, due to the constraints from the optical photometry and the orbital parameters (a companion >8 M$_{\odot}$ would require an extremely low inclination, $i < 9^{\circ}$). In the second case, (ii), 3X J0043 could be a LMXB similar to 4U 1822–37 (spin period: $P_{\mathrm{s}} = 0.59$ s and orbital period $P_{\mathrm{b}} = 0.23$ d; Jonker & van der Klis 2001) or to the ultracompact binary 4U 1626–67 ($P_{\mathrm{s}} = 7.7$ s and $P_{\mathrm{b}} = 0.03$ d; Rappaport et al. 1977; Chakrabarty 1998). These systems display a peculiar NS rotational period, that is much longer than expected (i.e., at millisecond level) in LMXBs in the standard picture where LMXBs are the progenitors of millisecond pulsars. They also emit X-rays with a harder (compared with the bulk of LMXBs) power-law spectrum below 10 keV, together with a blackbody component. Their X-ray luminosity, reaching a few times 10^{37} erg s^{-1} at most (Orlandini et al. 1998; Sasano et al. 2014; Iaria et al. 2015), is fainter than that observed in 3X J0043. However, we note that 4U 1822–37 is an accretion disc corona source, where the true X-ray luminosity is thought to be higher than observed, and may be at the Eddington limit for a NS (e.g. Bayless et al. 2010; Burderi et al. 2010; Iaria et al. 2015). The NS rotation period in 4U 1626–67 shows prolonged epochs of steady spin-up and spin-down, which is also the case of 3X J0043. The pulsed fraction displayed by 4U 1626–67 is much higher (~26–50%, Beri et al. 2014) than the one observed in 4U 1822–37 (~0.25% in the energy range 2–5.4 keV, while reaching 3% above 20 keV, Jonker & van der Klis 2001), and more similar to that of 3X J0043. However, both sources, and 4U 1626–67 in particular, have a much shorter orbital period. An accretion disk in a LMXB is allowed by the optical photometry, since the mean absolute magnitude expected from a disc dominating the optical emission in a LMXB can span a large range peaking at $M_V = 1$ (van Paradijs & van der Klis 1994). The possible optical association with a globular cluster in M 31 obviously favours a LMXB nature, with properties similar to those displayed by 4U 1822–37 or 4U 1626–67 in our Galaxy. Given the crowded field of 3X J0043, also a LMXB not associated with the globular cluster is possible.

The third possibility is that 3X J0043 is an object similar to Her X–1, an 'intermediate mass' X-ray binary (with a main-sequence A star companion) seen almost edge on, which has a spin period of 1.2 s for the NS and orbital period of 1.7 d (Tananbaum et al. 1972). For 3X J0043, a main sequence B and later spectral type star is a viable possibility (e.g. Schoenberner & Harmanec 1995). If the donor is a $\sim$2-M$_\odot$ star like in Her X–1, the association with a globular cluster can be ruled-out. Her X–1 displays an intensity and spectral variability with a on/off cycle of 35 days. The X-ray emission from Her X–1 is well described by a power-law with similar photon index as observed in 3X J0043 (below 10 keV); a soft excess, which can be described by a blackbody with temperature $kT \sim$ 130–140 eV, is also present, and is likely associated with the accretion disk (e.g. Burderi et al. 2000; Fürst et al. 2013). Although Her X–1 shows a lower X-ray luminosity than 3X J0043, reaching only $\sim$$10^{37}$ erg s^{-1}, its spectral and timing properties (hard power law below 10 keV, e.g. Oosterbroek et al. 1997, and spin and orbital periods) are similar to 3X J0043, except for the 35-cycle which, at any rate, is due to the viewing angle of the system. Another argument which favors a system similar to Her X–1 is the very high observed luminosity, which can be produced more easily in an intermediate-mass system rather than in a LMXB, where the mass accretion rate predicted from the secular evolution is in general small (Verbunt 1993).

We finally notice that if the NS in 3X J0043 is spinning at, or close to, the equilibrium period (i.e. when the magnetospheric radius equals the corotation one), as it is suggested by the alternating episodes of spin-up and -down, we can infer a rough estimate of the magnetic field strength of $\approx$$1.3 \times 10^{12}$ G, similar to those of Her X–1 and 4U 1626–67 (e.g. Bildsten et al. 1997). Such value is high with respect to the typical magnetic field inferred for radio pulsars in globular clusters.

3X J0043 is to our knowledge the first NS in M 31 for which the spin period has been found. While the precise nature of the system remains unclear, it is certainly an unusual source. We propose two alternatives for 3X J0043: it could be either a peculiar LMXB pulsar (possibly within the globular cluster), similar to 4U 1822–37 or 4U 1626–67, or an intermediate-mass binary system akin to Her X–1, possibly observed at low inclination (given the absence of orbital modulation of its X-ray flux). In this latter case, the analogy goes further to a similar orbital period.

ACKNOWLEDGEMENTS

EXTraS is funded from the EU's Seventh Framework Programme under grant agreement n. 607452. This research is based on observations obtained with *XMM–Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. We also used data from the NASA/ESA *HST*, obtained from the data archive at the STScI (operated by AURA Inc. under NASA contract NAS 5-26555). The Digitized Sky Survey was produced at the STScI under US Government grant NAG W-2166. We are grateful to R. Iaria for his constructive comments, and we thank R. Gualandi for the optical spectra obtained at the 152-cm Cassini telescope at Loiano during technical nights. LS acknowledges the PRIN-INAF 2014 grant.

REFERENCES

Bayless A. J., Robinson E. L., Hynes R. I., Ashcraft T. A., Cornell M. E., 2010, ApJ, 709, 251
Beri A., Jain C., Paul B., Raichur H., 2014, MNRAS, 439, 1940
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Bildsten L. et al., 1997, ApJS, 113, 367
Burderi L., Di Salvo T., Riggio A., Papitto A., Iaria R., D'Aì A., Menna M. T., 2010, A&A, 515, A44
Burderi L., Di Salvo T., Robba N. R., La Barbera A., Guainazzi M., 2000, ApJ, 530, 429
Chakrabarty D., 1998, ApJ, 492, 342
De Luca A., Salvaterra R., Tiengo A., D'Agostino D., Watson M. G., Haberl F., Wilms J., 2015, in Swift: 10 Years of Discovery, Caraveo P., D'Avanzo P., Gehrels N., Tagliaferri G., eds., Vol. 233, Proc. Sci., p. 135
Enoto T. et al., 2014, ApJ, 786, 127
Evans I. N. et al., 2010, ApJS, 189, 37
Fürst F. et al., 2013, ApJ, 779, 69
Hobbs G. B., Edwards R. T., Manchester R. N., 2006, MNRAS, 369, 655
Høg E. et al., 2000, A&A, 355, L27
Holland S., 1998, AJ, 115, 1916
Iaria R. et al., 2015, A&A, 577, A63
Israel G. L., Stella L., 1996, ApJ, 468, 369
Jonker P. G., van der Klis M., 2001, ApJ, 553, L43
Kaaret P., 2002, ApJ, 578, 114
Lange C., Camilo F., Wex N., Kramer M., Backer D. C., Lyne A. G., Doroshenko O., 2001, MNRAS, 326, 274
Massey P., Olsen K. A. G., Hodge P. W., Strong S. B., Jacoby G. H., Schlingman W., Smith R. C., 2006, AJ, 131, 2478
Oosterbroek T., Parmar A. N., Martin D. D. E., Lammers U., 1997, A&A, 327, 215
Orlandini M. et al., 1998, ApJ, 500, L163
Pietsch W., Freyberg M., Haberl F., 2005, A&A, 434, 483
Ransom S. M., 2001, PhD thesis, Harvard University
Rappaport S., Markert T., Li F. K., Clark G. W., Jernigan J. G., McClintock J. E., 1977, ApJ, 217, L29
Rosen S. R. et al., 2015, A&A, submitted (preprint: astro-ph.HE/1504.07051)
Sasano M., Makishima K., Sakurai S., Zhang Z., Enoto T., 2014, PASJ, 66, 35
Schoenberner D., Harmanec P., 1995, A&A, 294, 509
Shaw Greening L., Barnard R., Kolb U., Tonkin C., Osborne J. P., 2009, A&A, 495, 733
Stiele H., Pietsch W., Haberl F., Hatzidimitriou D., Barnard R., Williams B. F., Kong A. K. H., Kolb U., 2011, A&A, 534, A55
Strüder L. et al., 2001, A&A, 365, L18
Supper R., Hasinger G., Lewin W. H. G., Magnier E. A., van Paradijs J., Pietsch W., Read A. M., Trümper J., 2001, A&A, 373, 63
Tananbaum H., Gursky H., Kellogg E. M., Levinson R., Schreier E., Giacconi R., 1972, ApJ, 174, L143
Trudolyubov S., Priedhorsky W., 2004, ApJ, 616, 821
Turner M. J. L. et al., 2001, A&A, 365, L27
van Paradijs J., van der Klis M., 1994, A&A, 281, L17
Verbunt F., 1993, ARA&A, 31, 93
Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Table 1. Logbook of the *XMM–Newton* observations used in this work.

This paper has been typeset from a TEX/ LATEX file prepared by the author.

Table 1. Logbook of the *XMM–Newton* observations used in this work.

Obs. ID	Start date	Exposure[a] (ks)		Off-axis[b] (arcmin)	Count rate[c] (10^{-2} counts s^{-1})
0112570601	28-12-2000	13.3	(8.8)	15.8	1.97 ± 0.17
0112570101	06-01-2002	64.3	(48.3)	15.9	2.58 ± 0.08
0402560901	26-12-2006	61.9	(38.3)	14.7	3.39 ± 0.10
0405320701	31-12-2006	15.9	(12.2)	15.5	3.47 ± 0.19
0405320801	16-01-2007	13.9	(10.5)	15.5	3.76 ± 0.21
0405320901	05-02-2007	16.9	(13.1)	15.6	3.56 ± 0.19
0505720201	29-12-2007	27.5	(22.2)	15.4	3.77 ± 0.14
0505720301	08-01-2008	27.2	(21.7)	15.5	3.08 ± 0.13
0505720401	18-01-2008	22.8	(17.4)	15.6	2.37 ± 0.14
0505720501	27-01-2008	21.8	(9.5)	15.5	3.07 ± 0.21
0505720601	07-02-2008	21.9	(17.0)	15.6	3.10 ± 0.16
0551690201	30-12-2008	21.9	(15.8)	15.4	3.04 ± 0.15
0551690301	09-01-2009	21.9	(16.8)	15.5	3.13 ± 0.15
0551690401	15-01-2009	27.1	(3.1)	15.5	2.78 ± 0.33
0551690501	27-01-2009	21.9	(12.9)	15.5	3.70 ± 0.19
0551690601	04-02-2009	26.9	(7.8)	15.6	3.03 ± 0.22
0600660201	28-12-2009	18.8	(14.4)	15.5	3.50 ± 0.18
0600660301	07-01-2010	17.3	(13.2)	15.5	2.58 ± 0.16
0600660401	15-01-2010	17.2	(10.3)	15.5	2.53 ± 0.18
0600660501	25-01-2010	19.7	(10.2)	15.5	3.67 ± 0.21
0600660601	02-02-2010	17.3	(11.5)	15.6	3.01 ± 0.18
0650560201	26-12-2010	26.9	(17.0)	15.4	2.10 ± 0.13
0650560301	04-01-2011	33.4	(20.3)	15.5	3.34 ± 0.14
0650560401	15-01-2011	24.3	(9.2)	15.5	3.25 ± 0.21
0650560501	25-01-2011	23.9	(6.2)	15.6	2.49 ± 0.24
0650560601	03-02-2011	23.9	(14.2)	15.6	2.80 ± 0.16
0674210201	28-12-2011	20.9	(16.6)	15.4	1.61 ± 0.12
0674210301	07-01-2012	17.3	(11.6)	15.5	1.79 ± 0.14
0674210401	15-01-2012	19.9	(14.4)	15.5	1.81 ± 0.13
0674210501	21-01-2012	17.3	(13.5	15.6	1.15 ± 0.12
0674210601	31-01-2012	26.0	(15.2)	15.6	1.35 ± 0.11
0690600401	26-06-2012	122.4	(63.4)	1.8	7.11 ± 0.12
0700380501	28-07-2012	11.9	(8.9)	4.8	6.53 ± 0.30
0700380601	08-08-2012	23.9	(17.1)	4.8	5.49 ± 0.20
0701981201	08-02-2013	23.9	(15.7)	12.3	2.79 ± 0.15

[a] In parentheses we give the good observing time after dead-time correction and screening for soft proton flares.

[b] Radial off-axis angle of 3X J0043 from the boresight of the pn telescope.

[c] Net source count rate in the 0.3–10 keV energy band using the extraction regions described in the text; the values are not corrected for point spread function and vignetting effects.