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

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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 characterization 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, http://www.extras-fp7.eu, for details.

At the moment of writing, about 7400 *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 automatized 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 (>4.5σ), 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

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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

Notes. [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.

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 that a low mass X-ray binary (LMXB) in 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 (Section 2), as well as optical data (Section 3), we discuss the nature of this new X-ray pulsar (Section 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 summarized in Table 1. They span from 2000 December to 2013 February.

The raw observation data files 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. 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 ± 2 per cent), 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).

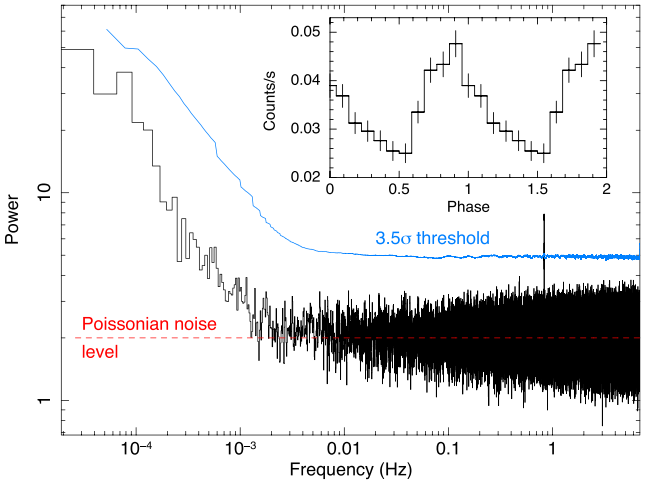

Figure 1. Fourier power spectrum from the 2000 December–2013 February pn data (0.5–10 keV; average of 36 Fourier transforms; $\Delta t \simeq 73$ ms, 262 144 frequencies). The blue line corresponds to the 3.5σ confidence level threshold for potential signals and was computed taking into account the number 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.

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 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, Edwards & Manchester 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 three 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 per cent.

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Table 2. Orbital parameters of 3X J0043.

Parameter	Value
Orbital period, P_b (d)	$1.27397828 \pm 0.00000071$
Epoch of ascending node, T_{asc} (MJD)	56104.7912 ± 0.0011
Projected semi-axis, $A_X \sin i$ (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

Notes. [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 $N_H = 7 \times 10^{20}$ 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 4500 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 $N_H < 7 \times 10^{20}$ 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: $N_H = (7 \pm 2) \times 10^{20}$ cm^{-2}, $\Gamma = 1.0^{+0.2}_{-0.1}$, $kT = 1.3^{+0.2}_{-0.1}$ keV and a blackbody radius $R_{BB} = 6.5^{+0.9}_{-0.7}$ km (at 780 kpc); the observed flux is $(4.8 \pm 0.2) \times 10^{-13}$ erg cm^{-2} s^{-1} (~40 per cent 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 2011 January/February. 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 normalization. Data are well fit by a power-law model with the N_H fixed at the M 31 value, when photon indices and normalizations 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 2012 August 8, was $(4.7 \pm 0.3) \times 10^{-13}$ erg cm^{-2} s^{-1} in the 0.3–10 keV energy band (luminosity: ~3.5×10^{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 2009 January 15. 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 $RA_{J2000} = 00^h43^m01\overset{s}{.}48$, $Dec._{J2000} = +41°30'16\overset{''}{.}9$ (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 2015 September 20, 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. 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 2005 February 19 (proposal ID: 10273) by the *Hubble Space Telescope* (*HST*) with the Wide Field Channel of the Advanced Camera for Surveys (ACS) instrument using the *F*555*W* filter (exposure time of 151 s; data set J92GA7VLQ), as well as the *F*814*W* filter (exposure time of 457 s; data set J92GA7VMQ). We retrieved geometrically corrected images produced by the on-the-fly reprocessing pipeline from the Mikulski Archive for Space Telescopes, 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 *F*814*W* filter and of 22.1 ± 0.1 in the *F*555*W* 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 an 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

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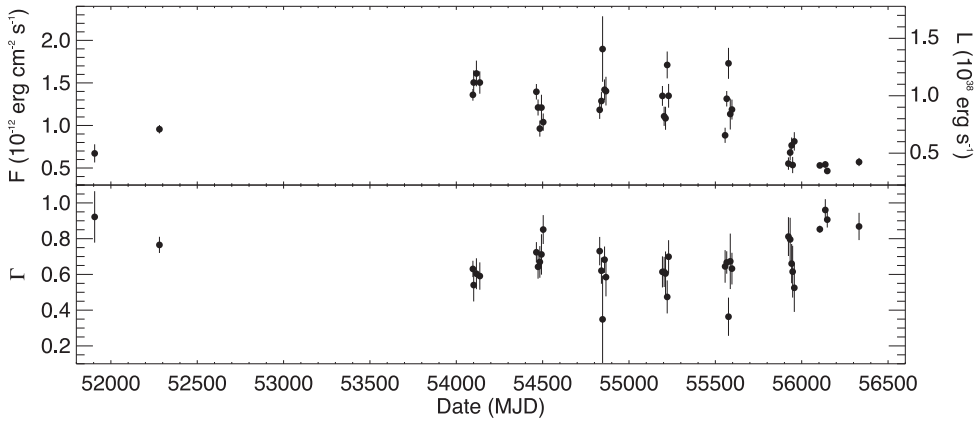

Figure 2. Long-term properties of 3X J0043 as observed with *XMM–Newton*. The flux (upper panel) and the photon index (lower panel) were derived in the 0.3–10 keV range from the power-law fit of all data sets with the $N_{\rm H}$ fixed at the value towards M 31 using the CFLUX model in XSPEC. In the upper panel, the right-hand 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 per cent for each observation.

time-scales of years, the X-ray flux varied by a factor $\approx$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 $\sim$10 per cent. 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 towards 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 $\sim$0.4 M$_{\odot}$.

If we consider the Corbet diagram of spin versus orbital periods of accreting X-ray binary (XRBs) (Enoto et al. 2014), there are essentially three possibilities among known objects for an XRB with a spin period of $\sim$1.2 s in a $\sim$1 d orbital period: (i) an 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).

An 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 an LMXB similar to 4U 1822−37 (spin period: $P_{\rm s} = 0.59$ s and orbital period $P_{\rm b} = 0.23$ d; Jonker & van der Klis 2001) or to the ultracompact binary 4U 1626−67 ($P_{\rm s} = 7.7$ s and $P_{\rm b} = 0.03$ 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 an 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 ($\sim$26–50 per cent; Beri et al. 2014) than the one observed in 4U 1822−37 ($\sim$0.25 per cent in the energy range 2–5.4 keV, while reaching 3 per cent 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 disc in an LMXB is allowed by the optical photometry, since the mean absolute magnitude expected from a disc dominating the optical emission in an 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 an 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 an 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 an on/off cycle of 35 d. 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;

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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 d cycle which, at any rate, is due to the viewing angle of the system. Another argument which favours 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 an 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.

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SUPPORTING INFORMATION

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

Table 1. Logbook of the *XMM–Newton* observations used in this work.
(http://www.mnrasl.oxfordjournals.org/lookup/suppl/doi:10.1093/mnrasl/slv194/-/DC1).

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