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Post-EXTraS discovery of a new pulsar in the LMC: a possible new magnetar candidate

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Abstract. We report the discovery of an X-ray pulsator in the Large Magellanic Cloud (LMC). The source (J0456) shows a coherent periodic signal with $P \simeq 7.25$ s, characteristic of a spinning neutron star (NS). J0456 is highly variable, with only one detection in various X-ray observations. The vast majority of (variable) X-ray pulsars in the LMC are found in binary systems with a Be-type companion star. Our spectroscopic observations of the only optical object that matches the X-ray uncertainty region, however, show that, if J0456 is an accreting NS, the companion is a G8-K3 star. This system would represent a novel binary evolutionary outcome in the MCs, but it would be hard to explain the lack of red noise in the power spectrum and the high pulsed fraction ($PF \simeq 86\%$) of J0456's spin signal within this scenario. These features are more common among isolated NSs. In particular, J0456 properties suggest that it is a magnetar, the second known in the LMC and the third known outside our galaxy.

Key words. Stars: Neutron – Galaxies: Individuals: Large Magellanic Cloud

1. Introduction

XMM-Newton (Jansen et al. 2001) is the currently active ESA mission dedicated to the observation of the Universe in the high-energy band. It is characterized by a unique combination of high throughput, large field of view (with a diameter $\simeq$ 30 arcmin) and long exposure times (up to $\simeq$ 130 ks), which allows the study of faint sources. Since its launch in 1999, its archive has steadily grown and it currently contains more than 650 thousands unique sources. The vast majority of them are serendipitous and unclassified, making the *XMM-Newton* archive the perfect target for data mining projects.

The Exploring the X-ray Transient and variable Sky project (EXTraS, see De Luca et al. 2021) was carried out with the aim of characterizing as many *XMM-Newton* serendipitous sources as possible and represents the most thorough living search for new X-ray pulsators. The satellite possesses three imaging cameras, one EPIC-pn (Strüder et al. 2001) and two EPIC-MOS (Turner et al. 2001) operating in the 0.3–12 keV band. EXTraS has led to the discovery of about 70 new pulsators and still counting (Rodríguez Castillo et al., in prep.). During the last run of the signal search, we identified a new X-ray pulsator in the Large Magellanic Cloud (LMC), i.e. 4XMM J045626.3-694723 (J0456 hereafter, see Imbrogno et al. 2023). With a period of $P \simeq 7.25$ s, J0456 most certainly represents a new spinning neutron star (NSs). J0456 has been detected only once, despite its position was covered by several *XMM-Newton*, *eROSITA*, *Swift* and *RXTE* observations, suggesting that J0456 is a highly variable source. In Sect. 2 of this proceeding we describe the MCs X-ray sources, focusing on those classes showing a similar variability. In Sect. 3 we report the results of our analysis on the *XMM-Newton* discovery observation and of our *SALT* observations of the only optical source compatible with the X-ray position. Finally, in Sect. 4 we discuss J0456 properties and conclude that the source is probably a new candidate magnetar, for which we missed the onset of the outburst.

2. The Magellanic Clouds X-ray variable sources

The LMC and the Small Magellanic Cloud (SMC) represent the two nearest star-forming satellite galaxies of the Milky Way. The MCs represents unique environments to test stellar evolution models. They host an unusally high number of X-ray pulsars, both isolated and in binary systems, due to recent star formation burst episodes (Antoniou et al. 2010; Antoniou & Zezas 2016). Among them, there are three classes of X-ray emitting NSs (both accreting and isolated) showing high flux variability.

2.1. Low-mass X-ray binaries

When the NS is accreting from a companion star with $M \lesssim 1\,M_\odot$, the system is classified as a Low-Mass X-ray Binary (LMXB). The accretion phase usually starts once the companion has filled its Roche Lobe and, given the long evolutionary timescale of less massive stars, it can last up to a few Gyr (Tauris & van den Heuvel 2006). During the accretion phase, the rotation of the NS can accelerate (spin-up) down to ms-long periods. Most pulsars in LMXBs are found with spin periods $P \lesssim 1$ s. However, when the companion is a K/M spectral-type giant, the accretion is driven by the companion winds, is less efficient and the pulsar shows much longer spin periods ($100 \lesssim P \lesssim 10^4$ s). These systems are known as Symbiotic X-ray Binaries (SyXB, see Yungelson et al. 2019)[1]. Both LMXBs and SyXBs show outburst phases during which the X-ray flux can be as high as 10^4 times their quiescience level, with typical 0.3–10 keV luminosities $10^{35}\,\mathrm{erg\,s^{-1}} \lesssim L_X \lesssim 10^{38}\,\mathrm{erg\,s^{-1}}$ (Bahramian & Degenaar 2023). Only one LMXB hosting a NS is known in the LMC, i.e. LMC X-2 (Agrawal & Nandi 2020), but it is a persistent source with a blue companion and the spin pulsation is unknown.

2.2. Be X-ray binaries

High-Mass X-ray Binaries (HMXBs) are systems in which the NS is accreting from a massive ($M \gtrsim 10\,M_\odot$) O/B spectral-type companion. The accretion phase in this case is usually driven by the companion wind and usually lasts for a few Myr (Tauris & van den Heuvel 2006). Given the shorter accretion time, pulsars in HMXBs are usually slower. The vast majority of HMXBs in the LMC (33 out of 40) are BeXRBs, i.e. HMXBs with a bright Be spectral-type companion star (Antoniou & Zezas 2016). Be stars are characterized by the presence of decretion disks surrounding their equator, produced by the matter expelled because of the fast rotation of the star. Correspondingly, during the NS orbital motion around the companion, high density gas region are crossed and the X-ray luminosity emitted by the NS increases (Orellana & Romero 2005). During this high active phases the 0.3–10 keV luminosity of the NS can increase up to a factor 10^5 (Haberl & Sturm 2016), typically in the range $10^{35}\,\mathrm{erg\,s^{-1}} \lesssim L_X \lesssim 10^{38}\,\mathrm{erg\,s^{-1}}$ for NS with $P_{spin} \simeq 10$ s.

[1] Although the companion in these systems is more massive than the classic LMXB definition, we considered them as LMXB following the XRBCat released by Avakyan et al. (2023).

2.3. Magnetars

The MCs also host two magnetars (Kaspi & Beloborodov 2017; Esposito et al. 2021), isolated NSs whose X-ray emission is powered by the release of the intense (10^{14} G $\lesssim B \lesssim 10^{16}$ G) internal magnetic fields. Only 30 magnetars are known and two of them, namely CXOU J010043.1–721134 (Lamb et al. 2002, 2003) and SGR 0526–66 (Mazets et al. 1979), lie in the SMC and LMC, respectively. Magnetar spin periods are all in the range $P \simeq 2 - 12$ s and, since their emission is powered at the expense of their internal energy, their rotation slows down (spin-down). Among the isolated NSs, they are the only ones that can reach X-ray 1-10 keV luminosities $L_X > 10^{34}$ erg s^{-1} (Esposito et al. 2020). Magnetars are usually discovered during outbursts, high active phases during which the luminosities can be as high as 1000 times their quiescence level, with typical 0.3–10 keV luminosities in the range 10^{34} erg s^{-1} $\lesssim L_X \lesssim 10^{36}$ erg s^{-1} (Coti Zelati et al. 2018) and lasting for few weeks/months.

3. J0456 analysis

All the uncertainties reported in this section are quoted at 1σ (68.3%) confidence range.

3.1. X-ray Analysis

J0456 has been detected by *XMM-Newton* during observation 0841660501 (October 2019, length of observation $T \simeq 47$ ks). In Fig. 1 we show the power density spectrum (PDS) of the combined EPIC-pn and EPIC-MOS light curves in the 0.3–10 keV band, together with the 3.5σ detection threshold computed following (Israel & Stella 1996). The spin signal at a period of $P \simeq 7.25$ s is clearly detected and has a significance of 11.3σ over the whole PDS. Through epoch-folding (Leahy et al. 1983) and phase-folding techniques, we obtained a refined estimate of the spin period $P = 7.25243(4)$ s. The folded profiles of the signal in the whole 0.3–10 keV, in the soft 0.3–2 keV and in the hard 2–10 keV bands are plotted in Fig. 2. The pulsed fraction PF (defined

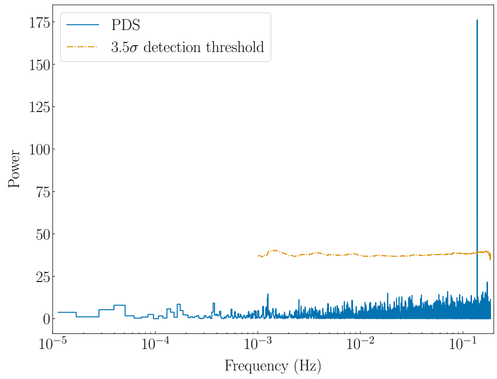

Fig. 1. J0456 PDS (blue) obtained from the combined EPIC-pn/EPIC-MOS light curves in the 0.3–10 keV band.

as the semi-amplitude of the sinusoid divided by the source average count rate) in each band is $PF_{0.3-10} = 85(6)\%$, $PF_{0.3-2} > 88\%$ (1σ lower limit) and $PF_{2-10} = 85(10)\%$, respectively. No significant upper limit on the spin period derivative could be derived from the available data.

In Fig. 3 we plot the unfolded spectrum of J0456. The X-ray emission can be modeled with a power-law which takes into account both the Galactic and an intrinsic absorption component. The value we inferred for the latter ($N_h \simeq 4.8 \times 10^{21}$) is consistent with the source being located in the LMC. Assuming for the source the same distance of the LMC ($d \simeq 50$ kpc, Pietrzyński et al. 2013), we derived an unabsorbed luminosity in the 0.3–10 keV band of $L_X \simeq 2.73 \times 10^{34}$ erg s^{-1}.

3.2. Optical Analysis

Within the 3σ positional uncertainty region of J0456, we identified only one possible optical counterpart, which we observed in November 2022 on two different nights with the South African Large Telescope (*SALT*, Buckley et al. 2006) with the RSS spectrograph (Burgh et al. 2003). The observed spectra from both nights in the 3800–5850 Å range are shown in Fig. 4. We highlighted the lines we identified and considered for the spectral classification, e.g. the Ca II H + Hϵ blend (3969), the CH G-band

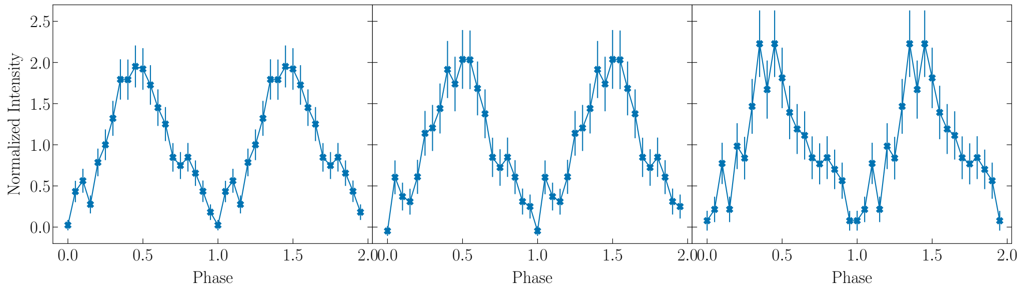

Fig. 2. Folded profile of J0456 spin signal in the 0.3–10 (left), 0.3–2 (center) and 2–10 keV band (right).

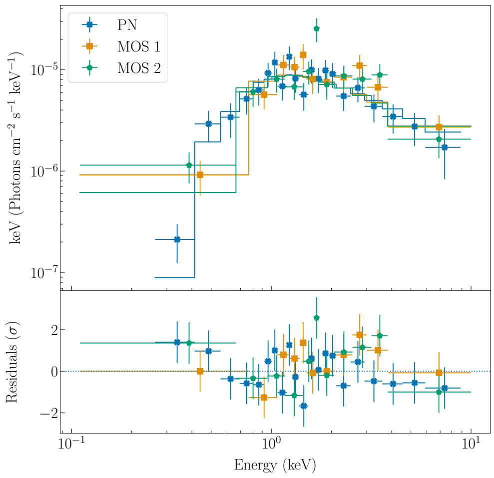

Fig. 3. Top panel: unfolded EPIC spectrum of J0456. Bottom panel: fit residuals.

(4300) and Fe I (4383). The latter lines, together with an estimated V-band absolute magnitude of $M_V \sim 0.2$ mag and the overall shape of the continuum, strongly suggest that the object is a G8-K3 star of luminosity class III.

4. Discussions and Conclusions

Without a second measurement of the spin period, it is not possible to obtain an unambiguous classification of J0456. If the candidate optical counterpart we identified is indeed the companion of J0456, this system would represent the first of its kind in the MCs. In fact, given the spectral classification of the star, J0456 would be a SyXB, the fastest by far. However, the lack of red noise in the PDS and the high pulsed fraction of the spin signal would be hard to explain in the case of an accreting source. These features are more commonly found in isolated NSs.

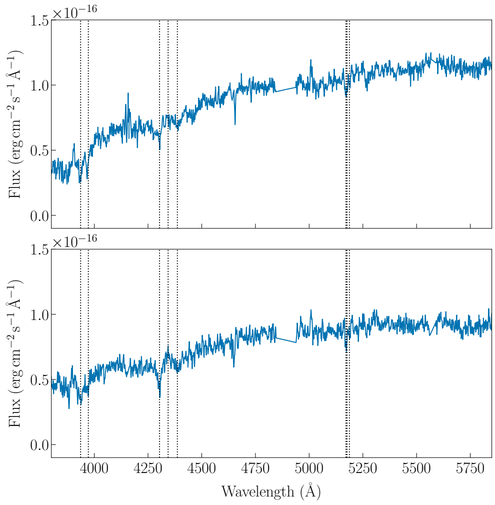

Fig. 4. Top panel: *SALT* spectrum of the possible optical counterpart of J0456 during the night of 2022 November 24. Bottom panel: as above, but during the night of 2022 November 25. The black dotted lines highlight the transitions we identified and considered for the spectral classification.

We compared the spin period, the pulsed fraction PF and the 0.3–10 keV luminosity L_X of J0456 with those shown by BeXRBs in the MCs, LMXBs/SyXBs with similar companions and magnetars during outbursts. We found that the combination of short P and low L_X is more often observed in magnetars, while accreting NSs at similar periods have a luminosity $L_X \gtrsim 10^{35}\,\mathrm{erg\,s^{-1}}$ (an order of magnitude higher than that of J0456). Moreover, high pulsed fractions ($PF > 80\%$) are more common in magnetars (2 out of our sample of 21) than in accreting pulsars (1 out of 80). Finally, we note that magnetar 1E 1048.1-5937 has a very similar combination of P, L_X and PF (6.46 s, $2.23\times10^{34}\,\mathrm{erg\,s^{-1}}$ and 91%, respectively; see Tiengo et al. 2005).

All these findings together favour the magnetar hypothesis: in this case, J0456 would represent the third known magnetar outside our galaxy. Further observations will help in nailing the nature of this source. In this respect, we started a monitoring campaign of J0456 with *Swift* with the aim of catching it during a high flux state, (hopefully) obtaining a new estimate of the spin period and, correspondingly, inferring its secular first period derivative. The latter measurement could help us discerning between the isolated (spin-down) and accreting (spin-up) scenario.

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References

Agrawal, V. K. & Nandi, A. 2020, MNRAS, 497, 3726

Antoniou, V. & Zezas, A. 2016, MNRAS, 459, 528

Antoniou, V., Zezas, A., Hatzidimitriou, D., & Kalogera, V. 2010, ApJ, 716, L140

Avakyan, A., Neumann, M., Zainab, A., et al. 2023, A&A, 675, A199

Bahramian, A. & Degenaar, N. 2023, in Handbook of X-ray and Gamma-ray Astrophysics. Edited by Cosimo Bambi and Andrea Santangelo, 120

Buckley, D. A. H., Swart, G. P., & Meiring, J. G. 2006, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 6267, Ground-based and Airborne Telescopes, ed. L. M. Stepp, 62670Z

Burgh, E. B., Nordsieck, K. H., Kobulnicky, H. A., et al. 2003, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4841, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes, ed. M. Iye & A. F. M. Moorwood, 1463–1471

Coti Zelati, F., Rea, N., Pons, J. A., Campana, S., & Esposito, P. 2018, MNRAS, 474, 961

De Luca, A., Salvaterra, R., Belfiore, A., et al. 2021, A&A, 650, A167

Esposito, P., Rea, N., Borghese, A., et al. 2020, ApJ, 896, L30

Esposito, P., Rea, N., & Israel, G. L. 2021, in Astrophysics and Space Science Library, Vol. 461, Timing Neutron Stars: Pulsations, Oscillations and Explosions, ed. T. M. Belloni, M. Méndez, & C. Zhang, 97–142

Haberl, F. & Sturm, R. 2016, A&A, 586, A81

Imbrogno, M., Israel, G. L., Rodríguez Castillo, G. A., et al. 2023, MNRAS, 524, 5566

Israel, G. L. & Stella, L. 1996, ApJ, 468, 369

Jansen, F., Lumb, D., Altieri, B., et al. 2001, A&A, 365, L1

Kaspi, V. M. & Beloborodov, A. M. 2017, ARA&A, 55, 261

Lamb, R. C., Fox, D. W., Macomb, D. J., & Prince, T. A. 2002, ApJ, 574, L29

Lamb, R. C., Fox, D. W., Macomb, D. J., & Prince, T. A. 2003, ApJ, 599, L115

Leahy, D. A., Elsner, R. F., & Weisskopf, M. C. 1983, ApJ, 272, 256

Mazets, E. P., Golentskii, S. V., Ilinskii, V. N., Aptekar, R. L., & Guryan, I. A. 1979, Nature, 282, 587

Orellana, M. & Romero, G. E. 2005, Ap&SS, 297, 167

Pietrzyński, G., Graczyk, D., Gieren, W., et al. 2013, Nature, 495, 76

Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18

Tauris, T. M. & van den Heuvel, E. P. J. 2006, in Compact stellar X-ray sources, Vol. 39, 623–665

Tiengo, A., Mereghetti, S., Turolla, R., et al. 2005, A&A, 437, 997

Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27

Yungelson, L. R., Kuranov, A. G., & Postnov, K. A. 2019, MNRAS, 485, 851