On the nature of newly discovered soft X-ray sources selected from the 2XMMp catalogue

Searching for thermally emitting isolated neutron stars

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Abstract

The group of seven thermally emitting and radio-quiet isolated neutron stars (INSs) discovered by ROSAT exhibits overall properties at variance from those of the bulk of rotation-powered radio pulsars. Within 1 kpc they appear as numerous as classical radio and gamma-ray pulsars. If their space density in the Galaxy is as large as in the solar vicinity, one would expect to detect a conspicuous concentration of soft X-ray sources at low galactic latitudes and towards distant OB associations. However, attempts to enlarge this group failed to confirm any reasonable candidate, although interesting X-ray sources have been discovered (for instance, Rutledge et al. 2008 *ApJ* 672: 1137). Aiming to find more distant thermally emitting INSs, we used the 2XMMp catalogue to select sources with no catalogued counterparts and with X-ray spectra similar to those of the ROSAT discovered INSs, but seen at larger distances and thus undergoing higher interstellar absorptions. In order to rule out alternative identifications such as an AGN or a CV, we obtained deep ESO-VLT and SOAR optical imaging for the X-ray brightest candidates. We report here on the optical follow-up results of our search and discuss the possible nature of our candidates. We focus particularly on the X-ray brightest source of our sample, 2XMM J104608.7-594306, observed serendipitously over six years by the XMM-Newton Observatory, which allowed us to carry out an analysis on its X-ray emission. A lower limit on the X-ray to optical flux ratio of ~ 500 together with a stable flux and soft X-ray spectrum make it the most promising thermally emitting INS candidate. Beyond the finding of new members, our study aims at constraining the space density of this population at large distances and at determining whether their apparently high local density is an anomaly or not.

Selection of candidates

The seven soft X-ray sources discovered in the ROSAT All-Sky Survey data constitute a nearby (few hundred parsecs) group of radio-quiet INSs characterized by long spin periods (few seconds) and high magnetic fields ($\sim 10^{13}-10^{14}$ G; see Kaplan 2008 *AIPC* 983: 331, Haberl 2007 *Ap&SS* 308: 181 for reviews). Proper motions studies (Motch et al. 2007 *Ap&SS* 308: 217, and references therein) have shown that these are cooling neutron stars of intermediate ages, 10^5-10^6 years, which have their origin in the nearby OB associations of the Gould Belt. We started a project aiming at finding more distant sources of the ROSAT kind with the goal to constrain their spatial density outside of the Gould Belt area. For that purpose, we searched the 2XMMp catalogue for new candidates using as criteria the absence of any correlated catalogued optical object (USNO, SDSS) and hardness ratios (HR) all consistent with blackbodies with $kT \leq 200$ eV undergoing absorptions in the range of $N_{\rm H} = 10^{19}-10^{22}\,{\rm cm}^{-2}$. We only consider non-extended and well detected sources with count rates above $\sim 0.01\,{\rm s}^{-1}$ in the EPIC PN camera. For each selected source, we visually checked the X-ray and optical images and searched for possible identifications in over 170 astronomical catalogues. Out of $7.5{\cdot}10^4$ serendipitous sources above the mentioned flux, we found no more than ~ 20 *good* candidates – i.e. intrinsically soft candidates not associated to any known optical or infra-red object – among which we selected eight of the brightest ones for follow-up optical observations during the years of 2007 and 2008, using the SOAR and ESO-VLT telescopes. In Figure 1 are shown the positions of these candidates in the ${\rm HR}_1\times {\rm HR}_2$ diagram, where ${\rm HR}_1 = \frac{(0.5\text{-}1.0)\,{\rm keV}-(0.2\text{-}0.5\,{\rm keV}}{(0.2\text{-}1.0)\,{\rm keV}}$, ${\rm HR}_2 = \frac{(1.0\text{-}2.0)\,{\rm keV}-(0.5\text{-}1.0)\,{\rm keV}}{(0.5\text{-}2.0)\,{\rm keV}}$.

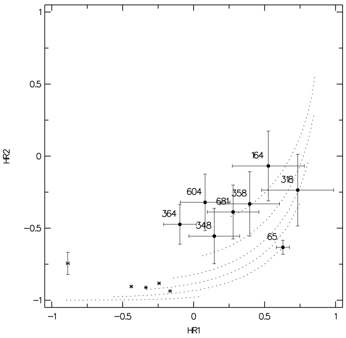

Figure 1. Positions of the eight INS candidates selected for optical follow-up in the ${\rm HR}_1\times {\rm HR}_2$ diagram (filled circles). Dotted curves represent blackbodies of $kT = 50-200$ eV undergoing column absorptions in the range $N_{\rm H} = 10^{19}-10^{22}\,{\rm cm}^{-2}$. The known INSs (crosses) occupy the lowest (less absorbed) part of the diagram while we expect our more distant candidates to be more absorbed and hotter than the known seven sources. All candidates have no known counterparts in other wavelengths and optical counterparts are expected to be fainter than at least $R\sim 21$.

Probable optical counterparts

Source	Cand	r arcsec	R	$U-B$	$B-R$	LR	$\log(f_{\rm X}/f_{\rm R})$
2XMM J121017.0-464609	164	1.35	20.126(4)	?	1.350(8)	8.8	0.18
2XMM J010642.3+005032	318	2.68	24.51(8)	?	$\gtrsim$0.5	1.3	2.19
2XMM J010642.3+005032	318	1.56	24.58(9)	?	$\gtrsim$0.6	1.2	2.22
2XMM J043553.2-102649	348	1.20	22.15(3)	-0.51(7)	0.94(6)	15.2	1.14
2XMM J031459.9-291816	358	0.67	21.379(13)	-0.12(6)	1.439(27)	32.1	0.44
2XMM J214026.1-233222	364	1.26	23.81(9)	-1.06(16)	1.09(14)	6.1	1.39
2XMM J125904.5-040503	604	1.34	21.629(28)	-1.09(3)	0.72(4)	25.5	0.45
2XMM J125045.7-233349	681	1.80	22.193(27)	-0.75(3)	0.74(3)	8.5	0.88

Table 1. Magnitudes, colours, likelihood ratios and logarithmic X-ray-to-optical flux ratios of the optical objects found in the error circles of our sample of candidates. Distances (relative to the X-ray source), LR and flux ratios refer to the objects found in the R images.

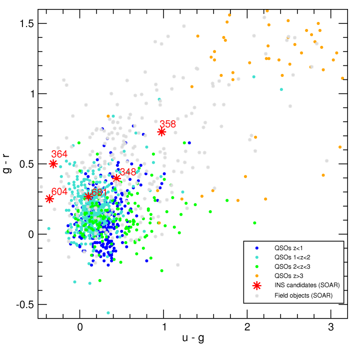

Figure 3. Colour-colour $g-r\times u-g$ diagram. Johnson-Morgan-Cousins transformation equations (Fukugita et al. 1996 *AJ* 111: 1748) were used to compute the magnitudes of our data in the SLOAN photometric system. Circles show the positions of identified QSOs (Richards et al. 2001 *AJ* 121: 2308) at different redshifts, while red and grey stars are our INS candidates and field objects observed with SOAR.

Optical follow-up

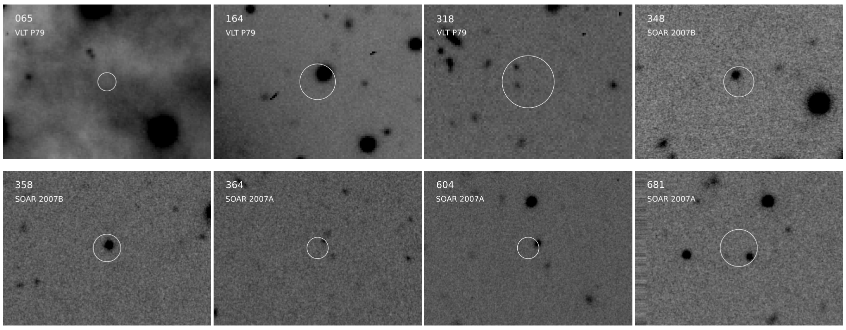

Figure 2. Finding charts. Upper diagrams show from left to right the fields of candidates 65, 164, 318 (observed with the VLT) and 348 while bottom diagrams show candidates 358, 364, 604 and 681, all observed with SOAR. All images are in the R filter.

Results

Deep optical imaging (Figure 2) has revealed the presence of at least one optical object inside the X-ray error circle (90% confidence level) of all our INS candidates but one, source 2XMM J104608.7-594306, dubbed candidate 65. In Table 1 we list the distance to the X-ray source, magnitude, colours, likelihood ratio (LR) and logarithmic X-ray-to-optical flux ratio (0.2 – 12 keV / R band, uncorrected for absorption) for each of the optical candidates. The LR of an association is defined as the ratio of the probability that, based on position, a given optical object is the true counterpart of the X-ray source to the probability that the object is just found by chance at this distance to the X-ray position. Although this ratio quantifies a given X-ray/optical association (objects with $LR \gg 1$ are more likely to constitute a true association) its calibration in terms of real probability of identification requires further analysis.

The strong UV excess exhibited by several of our candidates (348, 364, 604, and 681) are clearly consistent with those of AGN (see Figure 3). In spite of the more average colours of the optical candidates for sources 164 and 358, their high LR and $f_{\rm X}/f_{\rm R}$, similar to those of other AGN identified in XMM-Newton surveys (Barcons et al. 2007 *A&A* 476: 1203), leave no doubt that they are extragalactic sources as well. Source 318 has two equally likely weak optical candidates inside its large error circle with unusually high $\log(f_{\rm X}/f_{\rm R})\sim 2$. Although its position in the ${\rm HR}_1\times {\rm HR}_2$ diagram is compatible with a very soft and absorbed X-ray source, this source was detected in a short XMM exposure (as many of the other candidates) which, along with its low count rate yield large spectral errors.

Our best INS candidate is source 65, for which no optical optical counterpart is detected down to the limiting magnitude of our present data (Figure 4). Thanks to its proximity to the well-known double-star system Eta Carinae, it was observed serendipitously in several XMM-Newton observations carried out over a six year time interval. Its X-ray spectrum is well fitted by an absorbed soft blackbody of $kT\sim 110$ eV, with $N_{\rm H}\sim 4\cdot 10^{21}\,{\rm cm}^{-2}$. Although some possibly significant flux variations can be seen over this period of time (Figure 5), the bad location of the source on the EPIC CCDs in several observations (near gaps and at large off-axis distances) as well as remaining calibration uncertainties do not allow yet to conclude about a real effect. Its X-ray observed flux can be considered roughly steady around $\sim 1{\cdot}10^{-13}\,{\rm erg\,s^{-1}\,cm^{-2}}$.

2XMM J104608.7-594306

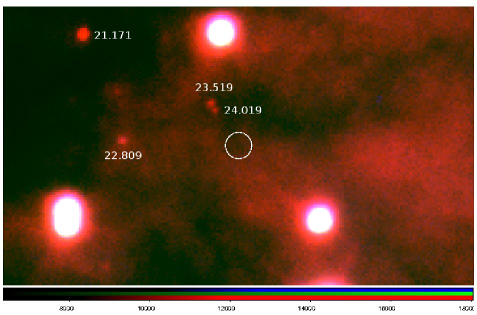

Figure 4. Composite BVR image of the field of candidate 65. No optical counterparts is detected at limiting magnitudes of $R\sim 25$, $V = 25.5$ and $B = 26$ ($2.5\,\sigma$ confidence level), defining a present lower limit of $f_{\rm X}/f_{\rm V}\sim 500$ (uncorrected for absorption). The R magnitudes of the surrounding faint objects are shown for comparison. The nebular diffuse emission (mostly Hα from the Carina Nebula) around the position of the X-ray source affects the photometry of faint objects especially in the R filter.

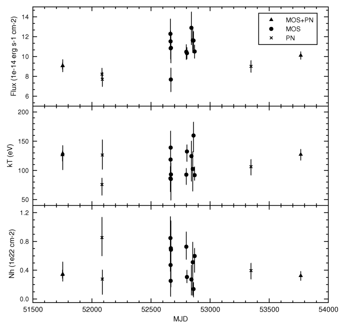

Figure 5. X-ray spectral analysis of candidate 2XMM J104608.7-594306, detected serendipitously in 17 different XMM observations. The best fit parameters shown are for an absorbed blackbody model with χ^2_ν between 0.6 and 1.4 (all parameters were allowed to vary freely; errors are 1 sigma). The observed flux is computed for the 0.15 – 3.0 keV energy band.

Conclusions

Our search for new thermally emitting INSs in the 2XMMp catalogue has revealed a handful of interesting and previously unknown soft X-ray candidates. Deep optical imaging revealed likely optical counterparts for six of them which, based on blue optical colours and $\log(f_{\rm X}/f_{\rm R})$ around $\sim 0-1$, identify them with AGN. Source 318 has no good optical candidate and should be further observed. Source 65 is, by far, our most promising candidate. The analysis of its X-ray emission, based on archival data obtained with non-optimal configurations, reveals an intrinsically soft energy distribution, apparently stable on long time scales. The derived $N_{\rm H}$ is consistent with that observed towards Eta Carinae and its cluster ($N_{\rm H}\sim 3{\cdot}10^{21}\,{\rm cm}^{-2}$; Leutenegger et al. 2009 *ApJ* 585: 1015). Scaling from RX J0720.4$-$3125 yields a distance of ~ 1.4 kpc which, considering the uncertainties on the spectral parameters, is probably compatible with the 2.3 kpc assumed for the Carina Nebula (Smith & Brooks 2007 *MNRAS* 379: 1279). Optical follow-up observations failed to reveal counterparts brighter than $R\sim 25$, $V = 25.5$ and $B = 26$ ($2.5\,\sigma$) which defines a $\log(f_{\rm X}/f_{\rm V})\gtrsim 2.7$ (uncorrected for absorption), implying that source 65 is a new thermally emitting INS.

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