Astron. Astrophys. 351, L53–L57 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

RX J0420.0–5022: an isolated neutron star candidate with evidence for 22.7 s X-ray pulsations*

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Received 2 September 1999 / Accepted 19 October 1999

Abstract. We report the discovery of a new isolated neutron star candidate, RX J0420.0–5022, showing evidence (4σ) for 22.7 s X-ray pulsations in ROSAT data. NTT observations of the field around the soft X-ray source do not reveal any likely optical counterpart brighter than B = 25.25 implying an X-ray to optical flux ratio of $> 10^{3.3}$ and ruling out other possible kinds of X-ray emitters. The X-ray spectrum of RX J0420.0–5022 can be described with blackbody emission with temperature kT of $\sim$57 eV and four ROSAT detections are consistent with no flux variations on time scales of years. The X-ray pulsations, if confirmed, make RX J0420.0–5022 the second long-period isolated neutron star candidate after RX J0720.4–3125. As for this latter source similar conclusions about the magnetic field strength of the neutron star can be drawn depending on evolutionary scenarios.

Key words: stars: individual: RX J0420.0–5022 – stars: neutron – X-rays: stars

1. Introduction

To date five candidates for isolated neutron stars (INS) were discovered in ROSAT data (RX J1856.6–3754, Walter et al. 1996; RX J0720.4–3125, Haberl et al. 1997; RX J0806.4–4123, Haberl et al. 1998; 1RXS J130848.6+212708, Schwope et al. 1999 and RX J1605.3+3249, Motch et al. 1999) which can be classified by their similar X-ray properties. The soft X-ray spectra are well represented by pure blackbody emission with temperatures kT between 50 and 120 eV and the X-ray flux is constant on time scales of months to 10 years. The X-ray brightest source, RX J1856.6–3754, could be identified with a faint blue object (V = 25.6) by Walter & Matthews (1997) on HST images and for the second brightest, RX J0720.4–3125, a likely counterpart with B = 26.1–26.6 was found (Motch & Haberl 1998, Kulkarni & van Kerkwijk 1998). The inferred extremely high X-ray to optical flux ratios $\log(f_x/f_{opt})$ of 4.8 and 5.3, respectively, exclude any known object other than an isolated neutron star. Similarly high lower limits for f_x/f_{opt} are derived from the faint brightness limits obtained for the other candidates (see table in Schwope et al. 1999).

The five candidates constitute the bright end of the log N – log S distribution of X-ray detected INS (with no detectable radio mission) of which up to several thousand were expected to be seen in the ROSAT all-sky survey (RASS, Blaes & Madau 1993, Colpi et al. 1993, Madau & Blaes 1994). The estimates were based on models of old neutron stars heated by the accretion of interstellar matter as proposed by Ostriker et al. (1970). From a compilation of available data on the number and space density of INS candidates and upper limits obtained from RASS follow-up identification programs Neuhäuser & Trümper (1999) concluded that the log N – log S curve lies between the theoretical expectations for middle-aged cooling neutron stars and old accreting neutron stars. They suggest that the larger number of expected accreting old neutron stars than observed is mainly caused by the assumed velocity distribution of the neutron stars.

From one of the five INS candidates X-ray pulsations were detected, indicating the spin period of the neutron star. The pulse period of 8.391 s found for RX J0720.4–3125 constrains the magnetic field strength of the neutron star. In the case of an accreting neutron star a weak field of less than 10^{10} G is derived for accretion to be possible (Haberl et al. 1997). A higher magnetic field strength in the past is required to spin down the neutron star to the present rate within a Hubble time *if* the neutron star was born with a typical spin period of 10 ms. Consequently this would indicate magnetic field decay and for a birth field strength of 10^{12} G decay time scales of $> 10^7$ y are derived (Wang 1997) for an old ($> 10^9$ y) neutron star. Alternatively RX J0720.4–3125 may prove to be a relatively young ($< 10^6$ y) cooling neutron star for which the argumentation from above would require a very high magnetic field strength of the order of 10^{14} G (Kulkarni & Kerkwijk 1998). The population of these "magnetars" was suggested to explain the properties of soft γ-ray repeaters (Kouveliotou et al. 1999 and references therein). The extremely strong magnetic field can suppress radio emis-

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* Partly based on NTT observations performed at the European Southern Observatory, La Silla, Chile

Table 1. ROSAT soft X-ray detections of RX J0420.0–5022 (0.1–2.4 keV)

Observation	exposure s	observed counts s^{-1}
Survey Jan. 23–25, 1991	193	0.12 ±0.03
PSPC Feb. 20, 1997	1538	0.11 ±0.01
HRI June 27–29, 1997	5782	0.021 ±0.002
HRI Dec. 15, 1997	1163	0.016 ±0.004

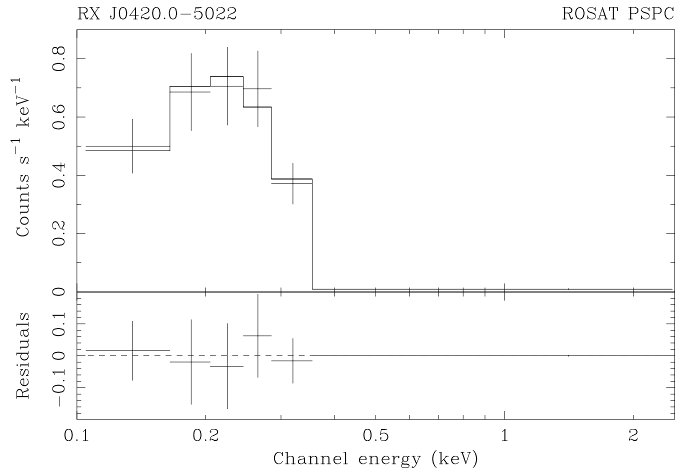

Fig. 1. The PSPC spectrum of RX J0420.0–5022 with the best fit blackbody model. The residuals are shown in the lower panel

sion and supply a significant source of heat, allowing magnetars to remain detectable in X-rays over longer times than ordinary pulsars (Heyl & Kulkarni 1998). However a doubling of the pulse period derivative observed in SGR 1900+14 casts doubt on the magnetar model as it requires a 100% increase of the magnetic field energy if magnetic dipole radiation were the primary cause of the pulsar spin-down (Marsden et al. 1999). Also the different X-ray spectrum of RX J0720.4–3125 in comparison to those of soft γ-ray repeaters would need to be explained by the magnetar model.

As long as the distribution of initial spin period / magnetic field strength is highly uncertain, conclusions on the evolution of these important neutron star parameters are tentative. The nature of RX J0720.4–3125 remains therefore unclear until an accurate measurement of the period derivative may further constrain the models.

In this letter we report on ROSAT X-ray and NTT optical observations of a new INS candidate, RX J0420.0–5022, which shows evidence for 22.7 s X-ray pulsations. Together with RX J0720.4–3125 it is only the second long-period INS candidate and their investigation is crucial for our understanding of their evolutionary status within the whole class of isolated neutron stars.

2. Observations

2.1. Soft X-rays

RX J0420.0–5022 was discovered as X-ray source in the ROSAT all-sky survey data and originally associated with the galaxy ESO 202-G008. It is included in the ROSAT all-sky survey bright source catalogue (1RXS J042003.1–502300, Voges et al. 1996) with 0.12±0.03 counts s^{-1}. Details on the ROSAT mission can be found in Trümper (1982) and the focal plane instruments PSPC (Position Sensitive Proportional Counter) and HRI (High Resolution Imager), both sensitive in the 0.1–2.4 keV energy range, are described by Pfeffermann et al. (1986) and David et al. (1993), respectively. From two follow-up HRI observations in June and December 1997 (the observations are summarized in Table 1) it became clear that the soft X-ray source is nearly 1′ away from ESO 202-G008 and unrelated. The best position was derived from the June 1997 HRI observation using the maximum likelihood technique of EXSAS (Zimmermann et al. 1994) to RA = $04^{h}\ 20^{m}\ 2\overset{s}{.}2$, Dec = -50° 22′ 46″ (J2000.0) with a 90% confidence error of 8″ (dominated by the 7″ systematic error of the attitude reconstruction). No other sources were detected in the HRI image which could be utilized for bore-sight correction.

RX J0420.0–5022 was serendipitously observed in a short PSPC pointing in February 1997 at an off-axis angle of 31′. The count rate is consistent with the survey detection and with the HRI detections in June and December 1997 (see Table 1 and below). The average PSPC spectrum (Fig. 1), although of low statistical quality, is very similar to the spectra of the known INS candidates without any significant number of counts above 0.4 keV. A power-law fit to the spectrum is acceptable but results in an unrealistic photon index of ∼10. The soft emission is well described by a blackbody model (kT = 57^{+25}_{-47} eV, column density 1.7×10^{20} cm^{-2} (0–8×10^{20} cm^{-2})) with an observed flux of 6.9×10^{-13} erg cm^{-2} s^{-1} (0.1–2.4 keV). Assuming a distance d for the source a bolometric luminosity of $L_{\rm bol} = 2.7\times10^{30}$ (d/100 pc)^2 erg s^{-1} is derived. Assuming an emission area with 10 km radius, the derived upper limit for the blackbody temperature (104 eV) yields un upper limit for the distance of 3.9 kpc. For the best fit temperature the distance is 700 pc but is further reduced for a smaller emitting area. Folding the blackbody model with the best fit parameters through the HRI energy response yields for the observed PSPC count rate (pointing) an expected HRI count rate of 1.9×10^{-2} counts s^{-1}. The PSPC position of RA = $04^{h}\ 20^{m}\ 1\overset{s}{.}6$, Dec = -50° 22′ 44″ (J2000.0, error of 17″) is 6.1″ away from the HRI position. The survey position is 16.5″ from the HRI position, also consistent within the errors. A formal average of the positions (weighting with errors) yields RA = $04^{h}\ 20^{m}\ 2\overset{s}{.}36$, Dec = -50° 22′ 49.″5 (7.″4 error), somewhat south of the HRI position.

A temporal analysis of the PSPC data using Fourier transformation and a Rayleigh Z^2 folding test (Buccheri et al. 1983) reveals evidence for periodic modulation of the soft X-ray flux with 22.69±0.03 s. The probability for a false detection of the period was derived to 7×10^{-5} corresponding to a 4 σ detection. The PSPC light curve folded by the pulse period is plotted in Fig. 2 and shows a sinusoidal semi-amplitude modulation of 43±14%. The folding analysis was also applied to the June

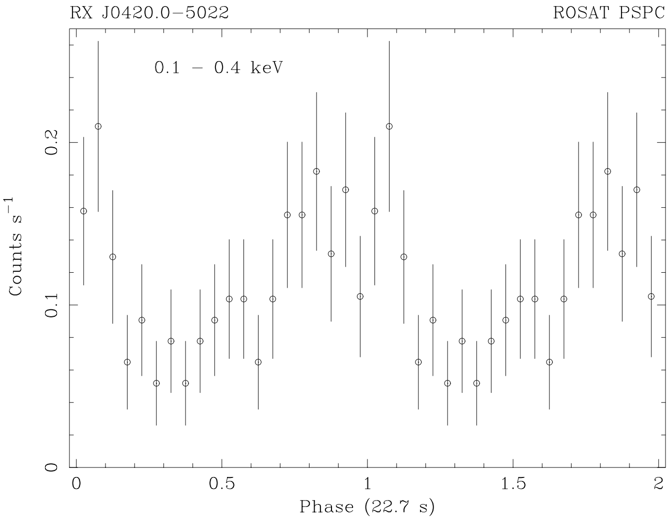

Fig. 2. PSPC light curve from February 20, 1997, folded with a period of 22.7 s, for clarity data points are repeated for a second period

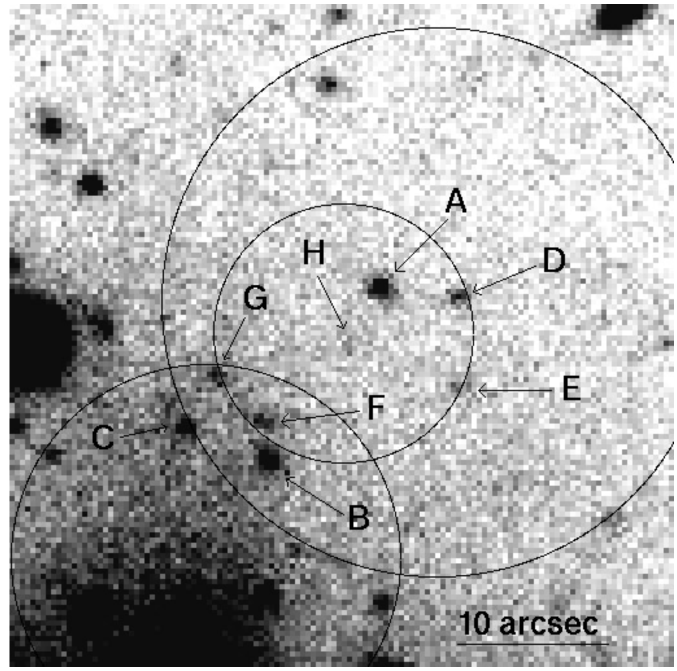

Fig. 3. The summed B and R images of the field of RX J0420.0–5022 corresponding to a total integration time of 1 hour and binned with a pixel size of 0.32″. The HRI, Survey and PSPC pointing 90% confidence error circle (8″, 12″and 17″radius respectively) are over-plotted. Positions of objects listed in Table 2 are also shown. North is to the top and East to the left

1997 HRI observation. The periodogram shows peaks around the expected period, supporting the reality of the modulation. However, the HRI observation was performed in five intervals unevenly spread over 49 hours causing a large number of alias periods spread over ∼0.5 s around the 22.7 s found from the PSPC observation (which was uninterrupted) and does not provide a better estimate for the period.

2.2. Optical

We observed the region of RX J0420.0–5022 with the ESO-NTT and SUSI2 on 1999 January 15. The combination of the two EEV CCDs yields a field of view of 5.′5 × 5.′5 with a pixel size of 0.″08. A total of 30 min in B and 30 min in R were accumulated using 10 min long individual exposures. The night was of photometric quality and observations of the standard field PG0942-029 allowed photometric calibration to an accuracy of ∼ 2%. Mean seeing was 1″ FWHM. Raw images were corrected for flat-field, bias and cleaned from cosmic-ray impacts using standard MIDAS procedures.

Fig. 3 shows the ROSAT HRI, PSPC and Survey error circles overlayed on the sum of the B and R images of RX J0420.0–5022 representing a total integration time of 1 hour. We also show in Fig. 4 and Fig. 5 the individual B and R summed images with the HRI error circle overlayed. Optical positions were computed using 8 stars extracted from the USNO A-1.0 catalogue and spread around the X-ray positions. The final astrometric accuracy should be that of the USNO catalogue, i.e. better than 1 arcsec.

Several faint objects labeled A to H on Fig. 3 are detected in or close to the HRI error circle. Table 2 lists the B and R magnitudes with one σ errors and information on image profile when possible.

The brightest object in the HRI error circle (object A) is stellar like and has a B-R colour index suggesting a remote G5V-K0V late type star. The next two brightest objects (B and D) located at the edge of the error circle appear clearly extended and are probable field galaxies. Among the remaining candidates, the brightest one which lacks reliable B-R colour index and spatial extent is object E with B = 25.25 ± 0.20. Our detection limit estimated from magnitudes of object H is B ∼ 26.5 and R ∼ 26.4.

3. Discussion

The soft X-ray source RX J0420.0–5022 is characterized by the same properties as the five previously published isolated neutron star candidates discovered in ROSAT data. A blackbody-like spectrum with kT = 57 eV and little interstellar absorption of $2{\times}10^{20}$ cm^{-2} are well within the range observed from the known candidates. No significant long-term flux variations were observed between ROSAT survey (1991, January 23–25) and three pointed observations in 1997.

Optical NTT imaging failed to identify the counterpart to the X-ray source. The brightest stellar-like object in the error circle has B = 24.44 ± 0.08 implying $\log(f_x/f_{opt}) \geq 3.0$ (using the observed X-ray flux of $6.9{\times}10^{-13}$ erg cm^{-2} s^{-1} and $f_{opt} = 10^{-0.4(B+13.42)}$ from Maccacaro et al. 1988). It exhibits a red B-R colour index, compatible with that of a remote late type star and can be ruled out on this basis. The next possible candidate has B = 25.25 ± 0.20 yielding a $\log(f_x/f_{opt})$ ratio of 3.3. This virtually excludes all possible kinds of soft X-ray emitters other than isolated neutron stars. In particular an identification with a hot white dwarf or with a very soft Seyfert-1 AGN (e.g.

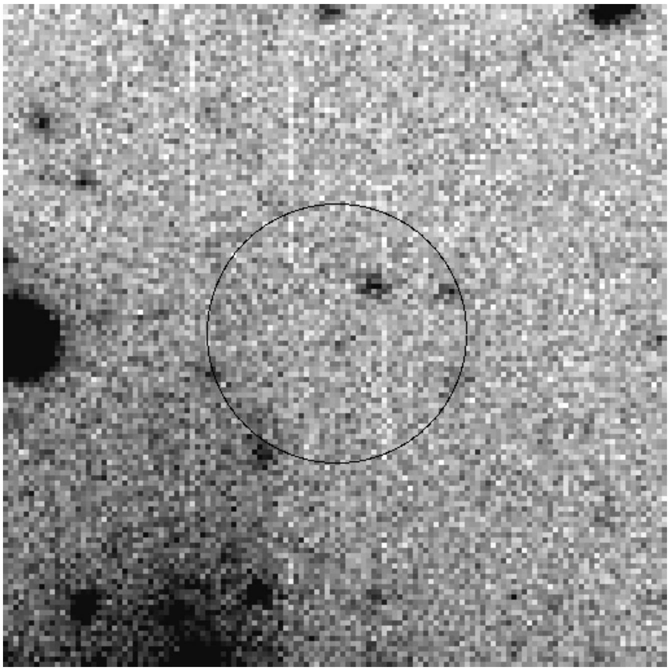

Fig. 4. The summed B images of the field of RX J0420.0–5022 corresponding to a total integration time of 30 min and binned with a pixel size of 0.32″. The HRI 90% confidence error circle (8″ radius) is over-plotted. North is to the top and East to the left

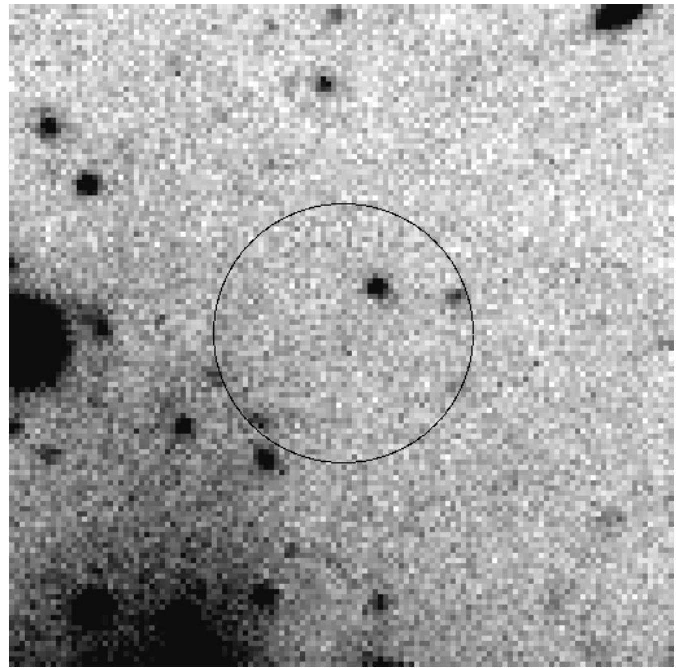

Fig. 5. The summed R images of the field of RX J0420.0–5022 corresponding to a total integration time of 30 min and binned with a pixel size of 0.32″. The HRI 90% confidence error circle (8″ radius) is over-plotted. North is to the top and East to the left

Grupe et al. 1998) seems to be excluded as this would imply the presence of an optically bright object in the error circle. A very distant white dwarf is also incompatible with the low observed absorption.

With 0.11 counts s^{-1} detected in the PSPC RX J0420.0–5022 is the faintest of the known INS candidates so far (see Schwope et al. 1999). It is a factor of 33 fainter than RX J1856.6–3754 which shows a similar blackbody temperature. Scaling the optical B magnitude of RX J1856.6–3754 by this factor yields an expected value of B $\sim$ 29.6 for RX J0420.0–5022, beyond the reach of our imaging. The serendipitous discovery near an unrelated object is the first of this kind and more INS may be unrecognized because of positional mis-identification. It is remarkable that it shows the same soft spectral properties as the previously found INS candidates like RX J0806.4–4123 and RX J1605.3+3249 which were discovered from dedicated searches of objects with such properties. This suggests that most INS have temperatures kT below ~ 120 eV and that the distribution is not strongly biased by selection effects.

In the ROSAT PSPC observation of RX J0420.0–5022 we detected X-ray pulsations with a significance of 4σ. If this is confirmed RX J0420.0–5022 would share this remarkable feature with RX J0720.4–3125. For none of the four other candidates periodic flux variations were found although it must be noted that small amplitude variations could not be detected in the available data due to insufficient statistics. The pulse period of 22.7 s for RX J0420.0–5022 is even longer than that for RX J0720.4–3125 (8.391 s) and the modulation is deeper (>29% compared to 12±2%).

Table 2. Optical magnitudes

Object	B	R	B-R	Profile
A	24.44±0.08	23.29±0.06	1.15±0.10	Stellar
B	24.54±0.10	23.52±0.06	1.02±0.12	Extended
C	-	23.68±0.07	-	Stellar
D	25.03±0.20	24.32±0.10	0.71±0.22	Extended
E	25.25±0.20	25.20±0.20	0.05±0.28	-
F	-	24.43±0.10	-	-
G	25.39±0.20	24.58±0.12	0.81±0.23	-
H	26.50±0.50	26.40±0.50	0.10±0.71	-

As in the case of RX J0720.4–3125 similar conclusions can be drawn for RX J0420.0–5022, based on the different scenarios conceivable for its evolution. If the X-rays are powered by accretion of interstellar matter then the magnetic field strength of RX J0420.0–5022 should be lower than 5.3×10^9 d_{100} G where d_{100} is the distance in units of 100 pc. This is a similarly low limit as obtained for RX J0720.4–3125 for a distance of a few hundred pc and would indicate magnetic field decay unless the neutron star was born with a relatively long spin period (Wang 1997). The lower temperature derived for RX J0420.0–5022 may indicate a factor of $\sim$4 lower accretion rate than for RX J0720.4–3125. This in turn increases slightly the allowed velocity of the neutron star relative to the ambient interstellar medium. However as in the case of RX J0720.4–3125 the relative velocity would probably be a few tens of km s^{-1}, well below 100 km s^{-1}.

In the magnetar model (Heyl & Hernquist 1998, Kulkarni & van Kerkwijk 1998) the factor 2.7 longer pulse period of RX J0420.0–5022 compared to RX J0720.4–3125 implies a different age and/or magnetic field strength of the neutron stars. Assuming that the neutron stars have spun down by magnetic dipole radiation the age is proportional to P^2/B^2. A similar magnetic field strength B would imply that RX J0420.0–5022 is a factor of 7.3 older than RX J0720.4–3125 while for similar age the magnetic field of RX J0420.0–5022 is stronger than that of RX J0720.4–3125 by the factor 2.7. A measure of the pulse period derivative RX J0720.4–3125 and RX J0420.0–5022 will be essential to determine the evolutionary status of these isolated neutron stars.

Acknowledgements. The ROSAT project is supported by the German Bundesministerium für Bildung und Forschung (BMBF/DLR) and the Max-Planck-Gesellschaft.

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