*Letter to the Editor*

# Constraints on optical emission from the isolated neutron star candidate RX J0720.4-3125[*]

**C. Motch**[1] **and F. Haberl**[2]

[1] Observatoire Astronomique, UA 1280 CNRS, 11 rue de l'Université, F-67000 Strasbourg, France
[2] Max-Planck-Institut für Extraterrestrische Physik, D-85740 Garching bei München, Germany

**Abstract.** Deep optical B band images of the ROSAT HRI error region of RX J0720.4-3125 reveal the presence of two faint stellar-like objects with B = 26.1 $\pm$ 0.25 and B = 26.5 $\pm$ 0.30. Exposures obtained through U, V and I filters are not sensitive enough to detect the two candidates and provide upper limits of U = 24.9, V = 23.2 and I = 21.9. These new observations virtually establish that RX J0720.4-3125 is a slowly rotating, probably completely isolated neutron star. The absence of an optical counterpart brighter than B = 26.1 seems incompatible with a neutron star atmosphere having a chemical composition dominated by Hydrogen or Helium. UBI photometry of field stars shows astonishingly little interstellar reddening in the direction of the X-ray source. Together with the small column density detected by the ROSAT PSPC, this suggests a mean particle density in the range of $n = 0.1$–$0.4$ cm$^{-3}$. Such average densities would imply very low velocities relative to interstellar medium ($v_{rel} \leq 10$ km s$^{-1}$) if the source were powered by accretion. These stringent constraints may be relaxed if the neutron star is presently crossing a small size structure of higher density or if the effective temperature of the heated atmosphere is overestimated by the blackbody approximation. Alternatively, RX J0720.4-3125 could be a young and highly magnetized cooling neutron star.

**Key words:** X-ray general – stars: neutron – stars: individual: RX J0720.4-3125

## 1. Introduction

Since the pioneering work of Ostriker et al. (1970), several studies have demonstrated that isolated old neutron stars (IONS) accreting matter from the interstellar medium should show up in great numbers at X-ray energies. As their expected effective temperatures are in the range of 10 to 300 eV, with soft X-ray

luminosities of up to $10^{32}$ erg s$^{-1}$ this population should be outstandingly visible in ROSAT survey and pointing data.

In spite of the large number ($10^8$ to $10^9$) of neutron stars created during the past life of the Galaxy, their identification in ROSAT data has been so far elusive. The optical emission from such objects may only arise from the small surface heated by accretion. With most telescopes currently available, the faint counterparts (V $\geq$ 25) cannot be recognized as such and accordingly, the density of IONS may only be constrained from the number of unidentified ROSAT sources. Optical campaigns carried out in selected ROSAT fields at low and high galactic latitudes yielded an unexpectedly small number of possible candidates (Motch et al. 1997, Zickgraf et al. 1997) which constrained the IONS population space density to be more than a factor 10 lower than predicted by current models (e.g. Blaes & Madau 1993).

However, a couple of bright soft X-ray sources were successfully associated with isolated neutron stars and in the X-ray brightest case (RX J1856.5-3754) an HST observation revealed the faint (V = 25.6) blue counterpart (Walter et al. 1997). The second X-ray brightest candidate, RX J0720.4-3125, exhibits the interesting feature to pulsate at a period of 8.39s (Haberl et al. 1997). The short rotational period implies a surface magnetic field of less than $10^{10}$G if the source is powered by accretion. This could provide the first good evidence for secular magnetic field decay in neutron stars (Haberl et al. 1997, Wang 1997) unless the decay results from a past episode of intense accretion occurred in a yet destroyed binary system.

## 2. Optical observations

Optical observations were carried out using the ESO-NTT in service mode for the U and B bands and the ESO-Dutch 0.9 m telescope for the V and I bands.

At the NTT we used SUSI equipped with the 1K$^2$ Tektronix TK 1024A CCD#42. The 24$\mu$ pixel size corresponds to 0.13$''$ on the sky. During the time interval from 1997 February 7 till April 4 we accumulated 2.5 h of observations in B and 3.5 h in U. Raw images were corrected for bias using over-scan regions and flat-fielded using sky images obtained at dawn. Individ-

ual 10 min long exposures were then stacked using a statistical method which rejected cosmic ray impacts. Finally, as the average FWHM seeing was about $0.9''$ merged images were rebinned to a $0.39''$ pixel size in order to gain sensitivity. Absolute photometric calibration and colour transformation was derived using standard fields from Landolt (1992) observed during four consecutive nights in February 1997.

At the ESO-Dutch 0.9 m telescope, we used the standard CCD adaptor equipped with Tektronics TK 512 CCD #33. This chip has a pixel size of $27\mu$, corresponding to $0.44''$ on the sky. A total of 17 min of observing time was accumulated in the V band on 1997 February 9 and 25 min in I band on February 11. CCD frames were corrected applying the same methods as for NTT data. The PG1323 field (Landolt 1992) was used for photometric calibration.

## 3. Optical content of the ROSAT HRI error circle

Following Haberl et al. (1997) we consider two possible boresight corrected HRI positions. Both positions are consistent one with each other and have each a 90% confidence radius of $3''$.

In the U, V and I band images, we fail to detect any object in or near the ROSAT error circles. We estimated the upper limit on the brightness of any source by generating at the ROSAT position artificial stellar images with a point spread function derived from a bright non-saturated stellar profile. Any star brighter than U = 24.9, V = 23.2 and I = 21.9 would have been detected.

The B band image reveals the presence of two objects, X1 and X2 in the merged error circles (see Fig. 1). Object X1 has B = $26.1\pm0.25$ and X2, B = $26.5\pm0.30$. The upper limit on the brightness of any other star is B = 26.5.

## 4. ISM properties towards RX J0720.4-3125

We show on Fig. 2 the U-B / B-I diagram for 37 faint objects located within $1'$ from the ROSAT HRI position together with mean relations for main sequence and evolved stars. Errors on individual colour indices take into account a 0.05 mag systematic uncertainty on the colour transformation. Because of CCD saturation we could not measure any of the bright stars located NE of the ROSAT position. B magnitudes are in the range of 17.8–23.6 with a peak between 20 and 23. Most objects have colour indices and magnitudes compatible with main sequence stars undergoing very little interstellar absorption. At the red end, few stars have colours suggesting some evolution. The couple of objects significantly departing from the main sequence relation may be extragalactic objects. UBV photometry of objects A, B and C (see Table 1) confirms the classification proposed by Haberl et al. (1997) on the basis of optical spectroscopy. A and B are G0 and G5 main sequence type stars whereas the colours of C suggest a K3 giant rather than a M dwarf type star.

The group of 15 stars with U-B $\leq$ 0.3 and B-I $\leq$ 2.0 are the most luminous unevolved objects in the field and probe absorption up to a mean distance of 14 kpc, i.e, well outside the galactic disc. By fitting a reddened population I main sequence relation to this group of stars we derive a most probable E(B-V)
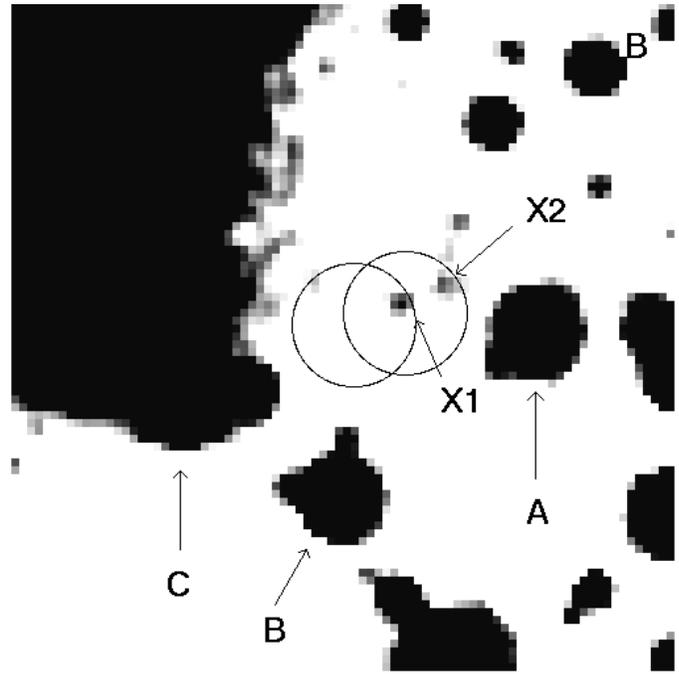


**Fig. 1.** ROSAT HRI error circles overlayed on the B image smoothed with a Gaussian filter ($\sigma = 0.35''$). The size of the image is about $33''$. North is to the top and east to the left

**Table 1.** UBV photometry of objects A,B and C

| Star | V | B-V | U-B |
|------|------|------|------|
| A | $20.00\pm0.05$ | $0.57\pm0.07$ | $0.00\pm0.07$ |
| B | $20.13\pm0.05$ | $0.70\pm0.07$ | $0.17\pm0.07$ |
| C | $19.91\pm0.05$ | $1.32\pm0.07$ | $1.50\pm0.10$ |

excess of 0.08 and put a 95% confidence upper limit of E(B-V) = 0.12 or $N_H$= 7.0 $10^{20}$ H atom cm$^{-2}$. As a large fraction of these high $z$ stars may be low metallicity population II subdwarfs, we also fitted a U-B / B-I relation assuming [ Fe / H ] = $-1.0$ and using calibrations provided by Cameron (1985). The population II relation gives a better fit to the photometry with a best E(B-V) excess of 0.04 and a 95% confidence upper limit of E(B-V) = 0.14. The group of 3 main sequence stars with B-I comprised between 2.5 and 2.8 and located at $\sim$ 2.2 kpc does not provide useful additional constraint at smaller distances.

In this direction the total galactic HI column density averaged over $0.5°$ is 1.89 $10^{21}$ H atom cm$^{-2}$. However, the IRAS $10\mu$ map shows a patchy structure with a hole only $4'$ SW to RX J0720.4-3125 suggesting that the actual $N_H$ towards RX J0720.4-3125 may well be as low as indicated by our field star photometry. Therefore, both the column density to the source, $N_H$ = $1.3\pm0.3$ $10^{20}$ H atom cm$^{-2}$ derived from X-ray spectral fitting and that from the source to the edge of the Galaxy are likely to be low. In particular, there is no evidence for any dense cloud behind the X-ray source as in the case of RX J1856.5-3754 (Walter et al. 1996).
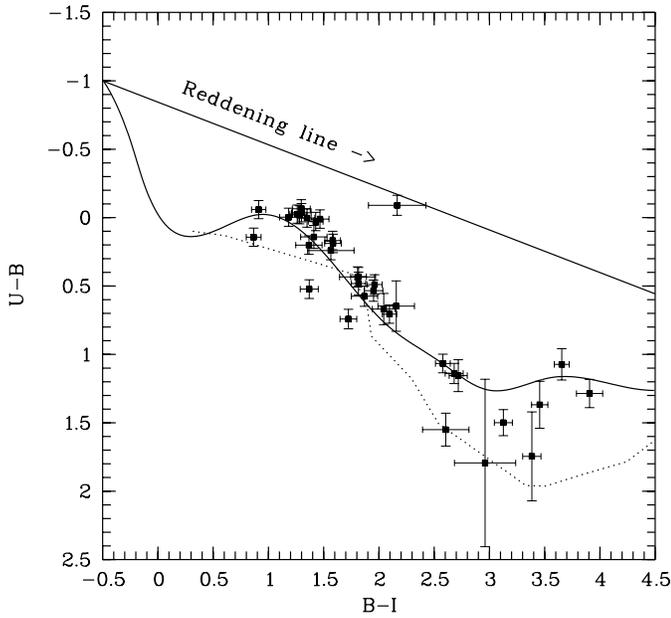
**Fig. 2.** U-B/B-I colour diagram for 37 stars located within $1'$ from the HRI position of RX J0720.4-3125. The relations for main sequence stars (solid line) and giant (dotted line) are plotted for comparison

If the $z$ distribution of HI along the direction of the X-ray source has the general shape of that given in Dickey & Lockman (1990) then a total $N_H$ of $7.0 \, 10^{20}$ H atom $cm^{-2}$ would imply an average particle density of $\sim 0.2 \, cm^{-3}$ at distances of a few hundred pc. A tenuous interstellar medium of comparable low mean density ($n \sim 0.2 \, cm^{-3}$) is also found towards the nearby (440 pc) open cluster Collinder 140, located only $1°$ away (Clarià & Rosenzweig 1978). Finally, RX J0720.4-3125 is less than $5°$ away from the interstellar tunnel of neutral free gas discovered by Welsh (1991). This rarefied region which has a diameter of 50 pc and a length of 300 pc is thought to be the farthest extension of the Local Bubble of hot gas.

PSPC data also imply $n = 0.4 \, (d/100pc)^{-1} \, cm^{-3}$ with $d$ approximately in the range of 100 to 440 pc (Haberl et al. 1997). Therefore, averaged over a large scale length, the ambient interstellar medium density is $n = 0.1$–$0.4 \, cm^{-3}$, significantly smaller than the mean galactic plane value ($n = 0.57 \, cm^{-3}$, Dickey & Lockman 1990).

## 5. Discussion

### 5.1. Is RX J0720.4-3125 a lonely neutron star?

The first important piece of information provided by the NTT observations is the absence of an optical counterpart brighter than B = 26.1 in the HRI error circles. This low optical flux definitely rules out any other kind of identification than with a neutron star. At a maximum distance of 440 pc, constrained by the blackbody fit to the PSPC energy distribution, an hypothetical companion to the neutron star would have an absolute I magnitude fainter than 13.7. Only stars later than M7V and less massive than $0.09 \, M_\odot$ may be faint enough to remain un-

detected. At 100 pc the hypothetical companion can only be a brown dwarf with M $\sim 0.075 \, M_\odot$ (Baraffe & Chabrier 1996). The low mass companion star would not have a wind intense enough to fuel the neutron star and the only mechanism which would allow the required mass transfer rate ($\dot{M} \sim 1.2 \, 10^{11} \, g \, s^{-1}$, $d = 100 \, pc$) is Roche lobe overflow. In such a case, we would expect substantial X-ray heating of the brown dwarf atmosphere and again an absolute I magnitude brighter than our limit. Therefore, we can probably conclude that the compact object is either completely isolated or at most accompanied by a very late M star or brown dwarf companion and that in all cases the neutron star does not accrete from the companion star.

### 5.2. Did we detect the optical counterpart of RX J0720.4-3125?

Extrapolating the blackbody detected at soft X-ray energies into the optical regime indicates that the neutron star should appear as a very faint but extremely blue object (B = 28.2, U-B = $-$ 1.3), 1.7 magnitude fainter than our B upper limit. However, there are several observational and theoretical arguments in favour of a brighter optical flux from RX J0720.4-3125. First, for a given soft X-ray flux, the optical magnitude depends very sensitively upon the chemical composition of the neutron star atmosphere. Rajagopal & Romani (1996) and Zavlin et al. (1996) have computed model atmospheres of low magnetic field neutron stars for various chemical compositions from pure Fe to pure H. These authors show that blackbody spectral fits to ROSAT PSPC data may yield temperatures and bolometric luminosities very different from those of model atmospheres. Atmospheres dominated by Hydrogen or Helium exhibit rather hard spectra in the 0.1–1.0 keV range which folded through the ROSAT PSPC and fitted by blackbody models give temperatures up to 3 times larger than the actual effective temperature of the neutron star. Similar effects albeit of lower amplitudes apply to a pure iron atmosphere. For instance, $T_{bb} = 79 \, eV$ (Haberl et al. 1997) would correspond to $T_{eff} = 63 \, eV$ for pure iron atmosphere and only $T_{eff} = 27 \, eV$ for Hydrogen dominated atmospheres (Rajagopal & Romani 1996). Furthermore, optical flux may be 1.5 to 5 magnitude above blackbody level, strongly depending on chemical composition (Pavlov et al. 1997, Walter et al., 1997). Our limit of B = 26.1 apparently rules out H or He dominated atmospheres.

On the observational side, Walter et al. (1997) report the HST discovery of the optical counterpart of the related source RX J1856.5-3754 with a V = 25.6 magnitude blue excess object (U-V = $-$ 1.2). The optical continuum is a factor 3.7 (1.4 mag) above the extrapolation of the ROSAT blackbody at 606 nm. Although the young pulsar physical conditions of Geminga may not allow direct comparison with RX J0720.4-3125, significant discrepancy between optical flux level and expected Rayleigh-Jeans continuum has been observed by Bignami et al. (1996). Therefore, it may well be that we already have enough sensitivity in B to detect the optical emission from the surface of the neutron star and that object X1 (B = 26.1) or X2 (B=26.5) is the counterpart of RX J0720.4-3125. Unfortunately, the V and U

magnitude limits are not deep enough to yield useful constraints on the colour indices of these candidates.

### 5.3. Is RX J0720.4-3125 powered by accretion from ISM or by neutron star cooling?

One intriguing feature of RX J0720.4-3125 is the low mean particle density of the medium in which the neutron star travels. There is some kind of contradiction in finding the second X-ray brightest isolated neutron star, believed to be powered by accretion from interstellar medium, in one of the lowest density regions close to the Sun. Assuming blackbody emission and Bondi-Hoyle accretion, $v_{rel}$, the relative velocity of RX J0720.4-3125 with respect to interstellar medium is given by:

$$(v_{rel}^2 + c_s^2)^{\frac{1}{2}} \; = \; 16.7 \, n^{\frac{1}{3}} \, d_{100}^{-\frac{2}{3}} \, km \, s^{-1}$$

with $c_s$ the sound velocity, $n$ the hydrogen number density of the interstellar medium and $d_{100}$ the distance to the source in units of 100 pc. If the sound velocity is of the order of 10 km s$^{-1}$ (e.g. Blaes & Madau 1993), and $n$ in the range of 0.1–0.4, then $v_{rel}$ must be amazingly low to account for the observed blackbody temperature derived from fits to PSPC data. In fact, the relative velocity reaches null values already at $d = 140$ pc ($n = 0.4$ cm$^{-3}$) and as close as $d = 70$ pc ($n = 0.1$ cm$^{-3}$).

HI structures are known to exist on scales ranging from 1 kpc to less than 100 AU (Dickey & Lockman 1990) and the particle density may be locally much larger or smaller than on average. Hot bubbles such as our Local Bubble can generate high density shells. The contributions of these dense regions to the total $N_H$ may be too small to be detected by optical reddening measurements while offering particle densities in excess of 1 cm$^{-3}$ on distances of 10 pc or more. A similar consideration may be applied to even smaller structures. Cloudlets with size of 1000 UA and densities of $10^3$ cm$^{-3}$ seem ubiquitous in the Galaxy (Watson & Meyer 1996). One could thus solve the density problem by supposing that RX J0720.4-3125 is now crossing the Local Bubble boundary or is immersed in one of these high density cloudlets. Long term variations of the X-ray luminosity could then soon give information on the size of the interstellar cloud surrounding the X-ray source. If the accretion luminosity is lower than estimated from the blackbody fit, the stringent constraints on relative velocity may be relaxed even in the case of a low density.

Alternatively, RX J0720.4-3125 could be a young cooling neutron star as proposed by Heyl & Hernquist (1998), a model which would not require any accretion at all. In this case, a very high polar field of $\sim 10^{14}$G must be present in order to slow down the neutron star by magnetic dipole radiation in only $\sim 3$ $10^5$ yr.

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