Astron. Astrophys. 351, 177–184 (1999)

ASTRONOMY AND ASTROPHYSICS

# The isolated neutron star candidate RX J1605.3+3249

**C. Motch[1,⋆], F. Haberl[2], F.-J. Zickgraf[1], G. Hasinger[3], and A.D. Schwope[3]**

[1] Observatoire Astronomique, UA 1280 CNRS, 11 rue de l'Université, 67000 Strasbourg, France
[2] Max-Planck-Institut für Extraterrestrische Physik, 85740 Garching bei München, Germany
[3] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

Received 10 May 1999 / Accepted 23 July 1999

**Abstract.** We report on X-ray and optical observations of a ROSAT X-ray source, RX J1605.3+3249, selected from the all-sky survey on the basis of its spectral softness and lack of bright optical counterpart. The ROSAT PSPC energy distribution is well fitted by a blackbody with kT = 92±6 eV and $N_H$ = $1.1\pm0.4\times10^{20}$ cm$^{-2}$. X-ray observations spanning 6.5 years fail to reveal any flux or spectral variability on any time scales. The ROSAT HRI error circle only contains a R = 23.25 M star which is unlikely to be associated with the X-ray source. We conclude that RX J1605.3+3249 is a probable nearby isolated neutron star detected from its thermal emission. The present data do not allow to unambiguously determine the X-ray powering mechanism, cooling from a young neutron star or heating by accretion from the interstellar medium onto an old neutron star. However, the long term stability of the X-ray flux favours the young neutron star hypothesis.

**Key words:** stars: individual: RX J1605.3+3249 – stars: neutron – X-rays: general

## 1. Introduction

Several arguments based on present metallicity of the interstellar medium, rate of supernovae and on properties of the observed radio pulsar population indicate that of the order of $10^8$ to $10^9$ old isolated neutron star (INS) should exist in the Galaxy. Ostriker et al. (1970) were the first to propose that a sizeable fraction of these old and radio-quiet neutron stars could be heated by accretion from interstellar medium and be again detectable by their far-UV and soft X-ray emission. Early modelling of this population by Treves & Colpi (1991) and Madau & Blaes (1994) led to the conclusion that re-heated old neutron stars should indeed appear in large numbers in soft and UV all-sky surveys with a possible concentration in the directions of highest interstellar medium densities, namely the galactic plane in general and more specifically molecular clouds.

Boosted by these predictions several optical identification campaigns of ROSAT X-ray and UV sources were initiated and it readily became clear that the number of possible isolated neutron star candidates was substantially below average model predictions (e.g., Manning et al. 1996, Motch et al. 1997, Danner 1998). However, four good isolated neutron star candidates were discovered so far in the ROSAT all-sky survey. These candidates share as common properties a soft X-ray spectrum with black body temperatures below 100 eV, no radio emission detected and very high $F_X/F_{opt}$ ratio in excess of $10^4$. The X-ray brightest of these candidates are RX J1856.5-3754 which was optically identified with a V=25.6 blue object (Walter et al. 1997) and the pulsating source RX J0720.4-3125 (Haberl et al. 1997) which has no counterpart brighter than B=26.1 (Motch & Haberl 1998, Kulkarni & van Kerkwijk 1998). Other good cases are RX J0806.4–4123 (Haberl et al. 1998) and 1RXS J130848.6+212708 (Schwope et al. 1999).

In the mean time, the possibility that a fraction of these candidates could rather be young neutron stars has gained considerable credit. The lack of detectable radio emission from these sources could be explained by a B, $P_{spin}$ position behind the radio pulsar death line or more simply by beaming effects which are stronger at long spin periods (Wang et al. 1999). Finally, RXTE observations have demonstrated that soft $\gamma$-ray repeaters are newly born neutron stars with extremely high magnetic fields (Kouveliotou et al. 1998) and belong to the population of magnetars proposed by Duncan & Thomson (1992). As radio emission can be quenched by the strong magnetic field, these objects may remain undetected by classical radio means and their birth rate could amount to 10% of that of ordinary pulsars (Kouveliotou et al. 1994). Since the primary store of energy in a magnetar is that in the magnetic field, B decay could constitute a significant source of heat, allowing magnetars to remain detectable in X-rays over longer times than ordinary pulsars (Heyl & Kulkarni 1998).

In fact, several of the INS found so far could be young neutron stars, perhaps descendant of soft $\gamma$-ray repeaters, rather than old accreting INS as originally thought. Detailed study of the few known INS and determination of their X-ray powering mechanism is therefore of high importance.

In this paper, we report on X-ray and optical observations of one of the X-ray brightest isolated neutron star candidates. The

*Send offprint requests to*: C. Motch

⋆ Visiting Astronomer, Canada-France-Hawaii Telescope operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France and the University of Hawaii.

source RX J1605.3+3249, also known as RBS 1556 (Schwope et al. 1999), was extracted from the ROSAT all-sky survey on the basis of its soft spectrum and lack of bright optical and radio counterpart.

## 2. Selection of isolated neutron star candidates from the ROSAT all-sky survey

Thanks to its soft sensitivity well suited to the detection of sources with $T_{\rm bb}$ = 20–100 eV, as expected from young cooling neutron stars or from old ones re-heated by accretion, the ROSAT all-sky survey offers a highly valuable database for detecting these elusive objects. In order to find candidates, we selected ROSAT all-sky survey sources displaying HR1 and HR2 hardness ratios compatible with intrinsically soft spectra slightly modified by a reasonable amount of interstellar absorption. Hardness ratios 1 and 2 are defined as

$$\mathrm{HR1} = \frac{(0.5-2.0)-(0.1-0.4)}{(0.1-0.4)+(0.5-2.0)}$$

$$\mathrm{HR2} = \frac{(1.0-2.0)-(0.5-1.0)}{(1.0-2.0)}$$

where (A-B) is the raw background corrected source count rate in the A−B energy range expressed in keV. Based on simulations of black body energy distributions folded with the ROSAT PSPC response we decided to extract all-sky survey sources having hardness ratios compatible (i.e. within one standard error value) with HR1 $\leq$ -0.25 and HR2 $\leq$ -0.5. This parameter space corresponds to $T_{\rm bb} \leq$ 100 eV and $N_{\rm H} \leq 4\times10^{21}$ to $3\times10^{20}$ cm$^{-2}$ for $T_{\rm bb}$ = 40 eV and $T_{\rm bb}$ = 100 eV respectively. Our observational strategy was then to identify all sources in large sky areas down to the faintest X-ray flux level possible in order to find new candidates and also efficiently constrain the space density of these objects. Results from this global study will be presented in a later paper. The possible INS nature of RX J1605.3+3249 = 1RXS J160518.8+324907 was discovered while identifying the northern sample. 1RXS J160518.8+324907 has a count rate of 0.875±0.041 cts/s, HR1 = −0.70±0.03 and HR2 = −0.58±0.10. To our knowledge, RX J1605.3+3249 is the brightest isolated neutron star candidate in the northern hemisphere.

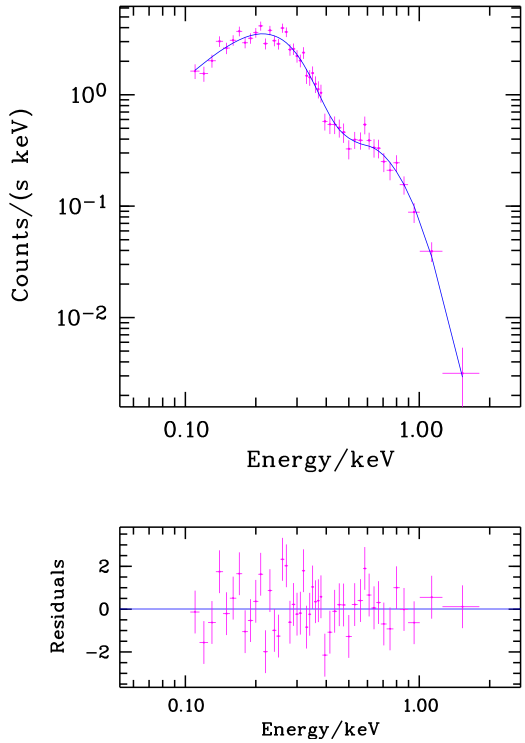


**Fig. 1.** Best blackbody fit to the PSPC count distribution of RX J1605.3+3249 with $T_{\rm bb}$ = 92 eV and $N_{\rm H}$ = 1.1 $10^{20}$ cm$^{-2}$

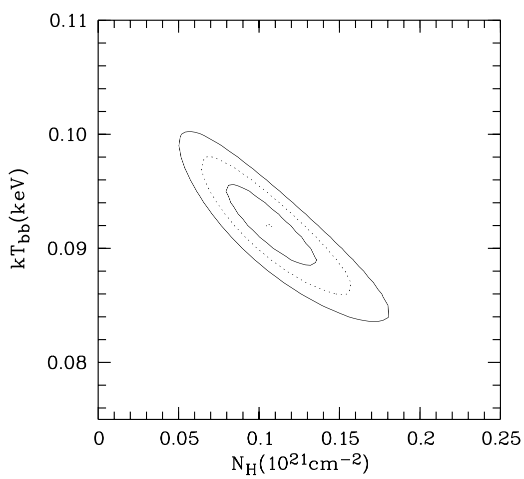


**Fig. 2.** $\chi^2$ contour plot showing the allowed parameter space for $N_{\rm H}$ and $T_{\rm bb}$ at the 1, 2 and 3 $\sigma$ confidence levels

## 3. ROSAT observations

ROSAT observed the field of RX J1605.3+3249 in pointed mode on two occasions. The first observation was carried out during the 1998 PSPC revival period from 1998 February 18 till 22 for a total exposure time of 4413 s. The second observation was performed with the HRI from 1998 March 2 to 4 and lasted 19307 s. The source was detected on both occasions.

### *3.1. X-ray spectral analysis*

The time averaged PSPC spectrum is well represented by a blackbody energy distribution with best fit parameters of $T_{\rm bb}$ = 92 eV and $N_{\rm H}$ = 1.1 $10^{20}$ cm$^{-2}$ ($\chi^2_{44}$ = 50.9). At the 95% confidence level, the allowed range is $T_{\rm bb}$ = 86–98 eV and $N_{\rm H}$ = 0.6–1.5 $10^{20}$ cm$^{-2}$. We show in Figs. 1 and 2 the best blackbody fit and the corresponding allowed spectral parameter range. The observed flux corresponds to a bolometric luminosity of $L_{\rm bol}$ = $1.1\times10^{31}$ ($d$/100 pc)$^2$ erg s$^{-1}$. Assuming isotropic blackbody emission, the source radius scales as $R$ = 1.1 km ($d$/100 pc). Black body temperature and line of sight absorption compare well with those observed from other INS candidates such as RX J1856.5-3754 ($T_{\rm bb}$ = 57±1 eV, $N_{\rm H}$ = 1.4±0.1 $10^{20}$ cm$^{-2}$;

**Table 1.** Flux measurements

| Date | Mode | Detector | PSPC cts/s | Note |
|---|---|---|---|---|
| 10-11 Aug 1991 | survey | PSPC | 0.875 ± 0.041 | HR1 = -0.70±0.03 HR2 = -0.58±0.10 |
| 18-22 Feb 1998 | pointed | PSPC | 0.900 ± 0.021 | HR1 = -0.66±0.02 HR2 = -0.68±0.04 |
| 02-04 Mar 1998 | pointed | HRI | 0.925 ± 0.020 | HRI cnt rate = 0.21 ± 0.01 cts/s |

Walter et al. 1996) and RX J0720.4-3125 ($T_{\rm bb}$ = 79±4 eV, $N_H$ = 1.3±0.3 $10^{20}$ cm$^{-2}$; Haberl et al. 1997).

### 3.2. Search for X-ray variability

Source flux appears remarkably constant over years to weeks time scales. We list in Table 1 the various source intensity measurements which are all compatible with a strictly constant emission. For the HRI observation we computed an equivalent PSPC count rate using the blackbody spectral description derived from the 1998 pointed PSPC observation. The energy distribution measured from hardness ratios did not change either between the almost 6.5 years elapsed from survey to pointed PSPC observations.

We also searched for both aperiodic and periodic variability in the ROSAT PSPC and HRI time-series. In all cases we failed to detect any significant variability. Applied to light curves binned in 100 s intervals the Kolmogorov-Smirnov test gives a 95% confidence upper limit of 43% on variability amplitude for the PSPC time series and does not provide useful constraints for the HRI data. Power spectrum analysis also fails to detect any periodic signal with an estimated upper limit of 50% and 36% full amplitude modulations for periods longer than 1 s in the PSPC and HRI data respectively. We note that if RX J1605.3+3249 had exhibited pulsations with an amplitude similar to those seen in RX J0720.4-3125 (24%, Haberl et al. 1997), we would not have detected them.

### 3.3. Source position

Considering the extreme optical faintness of the counterpart any attempt to identify the source obviously requires as good as possible X-ray localization. Although the positioning of the X-ray source on the HRI or PSPC instrumental reference grid can be accurate at the arcsec level for relatively bright sources such as RX J1605.3+3249, the uncertainty on the attitude of the satellite introduces a dominant 8–10 arcsec error. However, if enough identified and well localized sources are present in the field of view, it is possible to correct for the unknown attitude error and retrieve the intrinsic accuracy achievable with the given detector.

Above a Maximum Likelihood of 8, a total of 23 and 14 sources are detected in the PSPC and HRI fields of view respectively. We have cross-correlated the HRI source list with SIMBAD, FIRST and USNO-A2 catalogues. Among these detections, 4 PSPC and 6 HRI sources have a positive match in the searched catalogues. We also took into account the 4″ shift across the 40′ HRI field of view due to the pixel size being 0.9972±0.0006 instead of 1 arcsec (Hasinger et al. 1998). For one of the HRI and PSPC field source, RX J1605.5+3239, we had two possible identifications, either the nucleus of the spiral galaxy CASG 1345 or the FIRST radio source located 6.5″ away. Identifying the HRI source with the FIRST entry yields attitude correction vectors incompatible with those derived from other sources in the HRI field of view. We therefore assumed that the HRI source was identified with the galactic nucleus. We fitted to the differences between X-ray and optical positions expressed in arcsec, relations of the form $\alpha_{\rm X} - \alpha_{\rm opt}$ = 5″ ($X_{\rm IMA}$ − $X_{\rm Center}$) (1 − 0.9972) + Cte and $\delta_{\rm X} - \delta_{\rm opt}$ = 5″ ($Y_{\rm IMA}$ − $Y_{\rm Center}$) (1 − 0.9972) + Cte where $X_{\rm IMA}$ and $Y_{\rm IMA}$ are the position of the sources on the grid of 5″ size HRI pixels. The fit took into account the error on the positioning on the instrumental grid. We show in Fig. 3 the best fit obtained for the declination axis.

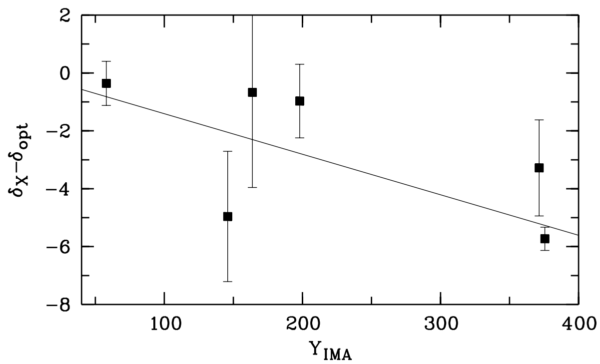


**Fig. 3.** X-ray to optical position offset as a function of HRI pixel number

Applying these relations to RX J1605.3+3249 moves the uncorrected HRI position by 0.4″ to the East and 3.6″ to the North to $\alpha$ = 16h 05m 18.66s and $\delta$ = +32° 49′ 19.7″ (2000.0 eq.) with a 1 $\sigma$ error of 0.64″. Using the 4 identified PSPC sources yields a compatible position at $\alpha$ = 16h 05m 18.75s and $\delta$ = +32° 49′ 17.8″ (2000.0 eq.) with a 1 $\sigma$ error of 3.4″. The HRI and PSPC pointed positions are well within the 90% confidence ROSAT survey error circle ($\alpha$ = 16h 05m 18.8s and $\delta$ = +32° 49′ 07.5″ (2000.0 eq.) with a 1 $\sigma$ error of 7.0″).

## 4. Optical data

### 4.1. Observations

First optical observations took place from 1998 April 14 to 17 using the Canada France Hawaii telescope. Images and spectra were obtained with the OSIS V instrument which provides image stabilisation and active guiding. With the 2048 × 2048 STIS2 CCD the pixel size is 0.156″ on the sky. We acquired

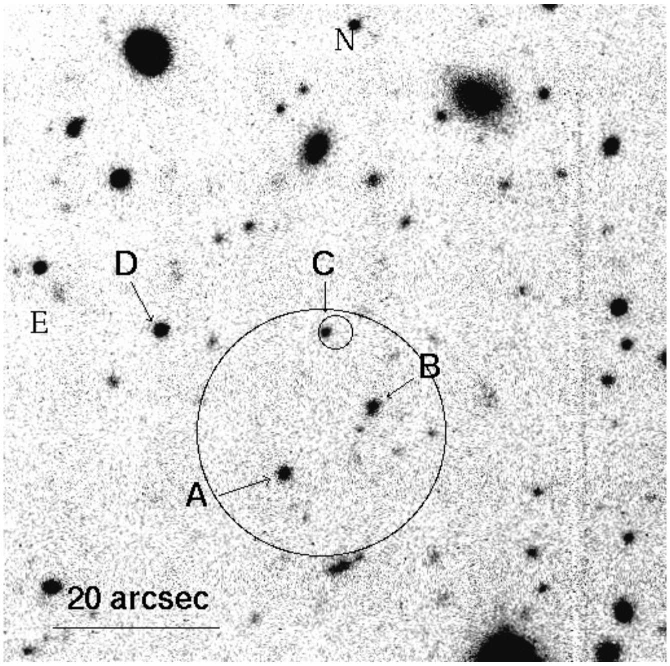


**Fig. 4.** The summed CFHT R band image showing the position of the ROSAT HRI attitude corrected error circle ($r_{90} = 2''$), the ROSAT PSPC survey error circle ($r_{90} = 15''$) and the 4 objects for which we obtained low resolution spectroscopy.

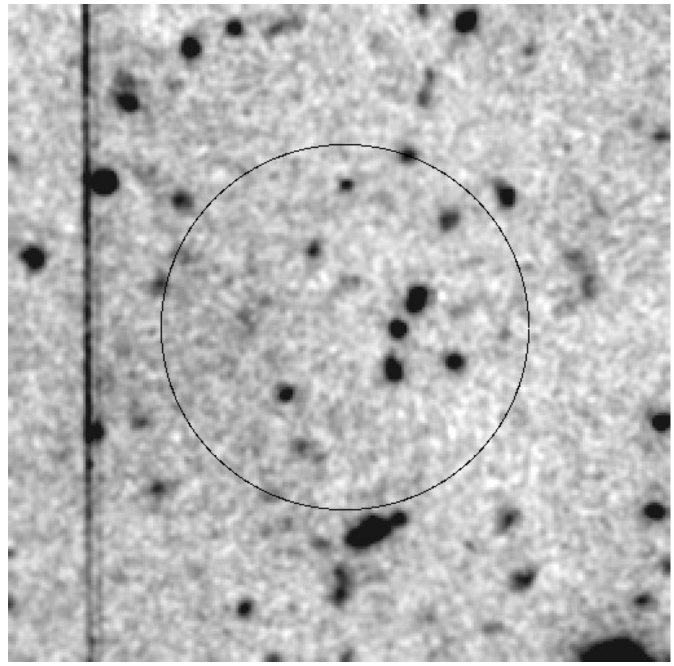

**Fig. 5.** The summed Keck B band image with the ROSAT PSPC survey error circle ($r_{90} = 15''$) overplotted. North is at top and East at left.

several 15 min long images through the B, R and I filters. Total exposure time amounts to 60 min in B, 75 min in R and 15 min in I. FWHM seeing was quite constant throughout the run with a mean value of $1.0''$. Images were corrected for bias and flat-fielded using standard MIDAS procedures. All nights were of photometric quality. Observation of standard stars in M92 (Christian et al. 1985) allowed to calibrate the images with respect to the Kron-Cousins BVRI system.

We also obtained low resolution spectroscopy of the 4 brightest optical objects named A,B,C and D and located inside or close to the ROSAT all-sky survey error circle. Wavelength calibration was derived from the observation of Hg/Ar arc spectra and the instrumental response was computed using the flux standard star Feige 34. The Multiple Object Spectroscopy mode of the OSIS instrument allowed the simultaneous acquisition of spectra from the 4 objects through $1''$ slits and using the V150 grism. This configuration yields a FWHM resolution of $\sim 2$ nm and a useful spectral range of 365 to 990 nm. We acquired 6 individual frames with exposure times ranging from 30 to 60 min. The total spectral exposure time is 225 min. Spectra were flat-fielded, wavelength calibrated, extracted and corrected for atmospheric absorption and instrumental response using standard MIDAS procedures.

Additional images were obtained with the Keck LRIS (Low-Resolution Imaging Spectrograph) on 1999 February 23. These observations took place under good sky conditions with a seeing around 0.9 arcsec. Two B and two R images of the field were taken with a total exposure time of 15 min in each filter. Using observations of one Landolt standard star field, a photometric calibration with estimated uncertainty of 0.1–0.2 mag was achieved.

### *4.2. Imaging data*

We show on Fig. 4 the summed CFHT R band image with the 90% confidence level ROSAT HRI and ROSAT survey error circles over-plotted. The Keck B image is displayed in Fig. 5. We calibrated astrometrically our CCD image using 5 USNO-A2 stellar like objects. The attitude corrected HRI 90% confidence error radius of $2''$ shown here includes the additional astrometric error of $0.7''$ arising from the CCD calibration. The only detectable object in the ROSAT HRI error circle is C.

R band image profile measurements reveal that objects A and B are resolved. A seems extended in all directions whereas B has a stellar-like core with diffuse emission towards the SE direction. On the other hand, objects C and D appear unresolved.

BRI photometry of objects A,B,C and D as derived from CFHT observations is listed in Table 2. Only object D is bright enough to be detected in the CFHT B band image. We estimate limiting magnitudes of $B \sim 24.6$ and $R \sim 25.0$ on the summed images.

Keck photometry of object C gives R = 23.3 and B-R = 2.6 consistent with CFHT observations. The limiting magnitudes of the Keck images are estimated to be $B \sim 27$ and $R \sim 26$.

### *4.3. Spectroscopic data*

In general, the signal to noise ratio of the average spectra is not good enough to unambiguously measure a redshift or detect the

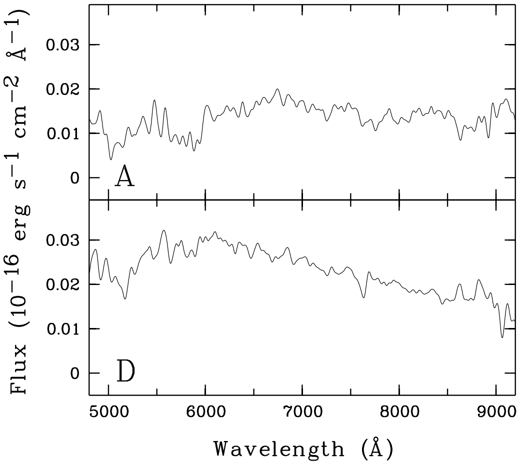


**Fig. 6.** Flux calibrated spectra of objects A and D. Spectra have been smoothed by a Gaussian filter with $\sigma$ = 18 Å

**Table 2.** BRI photometry of objects A,B,C and D derived from CFHT observations

| Star | B | R | I | R - I |
|---|---|---|---|---|
| A | - | 22.46±0.04 | 21.51±0.07 | 0.85±0.08 |
| B | - | 22.53±0.04 | 21.03±0.05 | 1.32±0.06 |
| C | - | 23.25±0.05 | 22.03±0.07 | 1.07±0.08 |
| D | 23.83 ±0.20 | 21.90±0.03 | 21.34±0.05 | 0.52±0.06 |

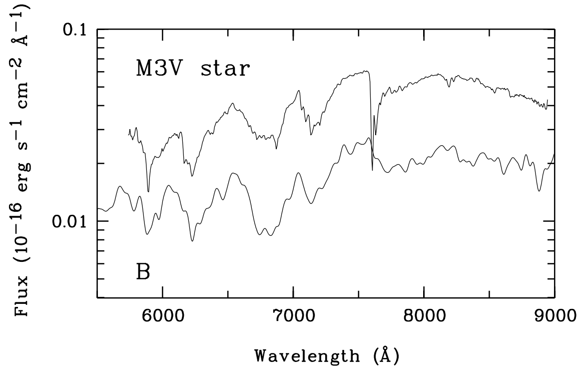


**Fig. 7.** Flux calibrated spectrum of object "B" (bottom) plotted together with that of a template M3V star (top). The spectrum of B is smoothed using a Gaussian filter with $\sigma$ = 18 Å

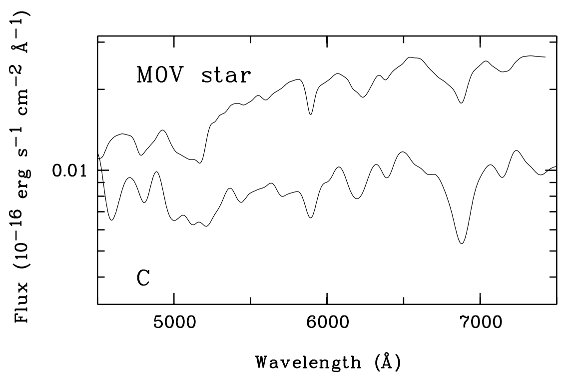


**Fig. 8.** Flux calibrated spectrum of object "C" (bottom) plotted together with that of a M0V (top). Both spectra were smoothed using similar Gaussian filters

presence of weak emission lines. Telluric absorption lines (e.g. the $\lambda$6800–6900 Å complex) are not pronounced.

Identifying the flux drop bluewards of 6000 Å in object A (see Fig. 6) with the Ca break leads to a redshift of $\sim$ 0.5. At this redshift, other spectral features such as G band, H$\beta$ and Mg band may be seen in the spectrum.

The spectrum of object B leaves hardly any doubt that the stellar-like core is in fact a dwarf M3-4 star, the extended emission being then a likely background field galaxy. We show on Fig. 7 the observed spectrum together with that of a comparison M3V star extracted from the atlas of Torres-Dodgen & Weaver (1993). The NaI line, TiO and CaH bands are clearly detected. Neglecting the contribution of the background galaxy, the R-I colour index is also consistent with that of a M3-4V star.

As object C is the only one detected in the small attitude corrected HRI error circle, special attention was given to its analysis. Being about 0.7 mag fainter than star B the spectral features of C are obviously less recognizable. There is however good evidence that C is also a M star, of slightly earlier spectral type than star B. For comparison, we show on Fig. 8 the flux calibrated spectrum of C together with that of a template M0V star extracted from the spectral atlas of Jacobi et al. (1984). The NaD line and the broad TiO molecular bands visible in the smoothed M0V spectrum can be also seen in object C. The similarity of the energy distributions is also striking and the R-I and B-R colour indexes of C are also consistent with a $\sim$ M2V star. All these evidences support the conclusion that C is a rather early M type star.

Finally, based on Ca break, H$\beta$ and NaD line positions, the spectrum of object D (Fig. 6) suggests an identification with a galaxy at $z \sim 0.3$.

## 5. Discussion

### *5.1. The nature of RX J1605.3+3249*

The position of object C in the attitude corrected HRI error circle is somewhat puzzling but may not be fully significant. At $l$ = 53°, $b$ = 48°, the surface density of stars brighter than R = 23.5 is 12,300 deg$^{-2}$ (Robin & Crézé 1986). There is therefore more than 1% probability that a star falls by chance in the 2$''$ radius error circle.

The photometric distance to the M2V star is $\sim$ 7 kpc. If the X-ray source were physically associated with the star, its radius would be $R \sim$ 80 km, i.e. too large for a neutron star and too small for a white dwarf. The emitting area could be compatible with a polar cap heated by accretion as seen in AM Her systems in which case, our optical observations could have been obtained during a low state. This explanation cannot be strictly ruled out, as the white dwarf could be cool enough in the low state ($T_{\rm eff} \leq$ 20,000 K) to remain undetected at B = 25.85 which is the B magnitude of object C. We also do not have enough spectral resolution to detect the emission lines which could reveal heating of the late M star by the white dwarf. However, the absence of X-ray and optical variability and the unusually hot temperature of RX J1605.3+3249 compared to those of black body components in polars make this possibility rather unlikely.

A hot white dwarf would have to be located at unrealisticly large distances ($d \sim 270$ kpc), although this distance may be overestimated by the black body fit. The black body temperature is also hot compared to that observed from the hottest known PG 1159 stars (e.g. Werner et al. 1996). Finally, if the high temperature of the white dwarf were due to nuclear burning at its surface, we would detect the heated accretion disc and mass donor star or the surrounding nebula such as in SMC N67.

In general, all classes of soft emitters else than neutron stars are difficult to reconcile with the observational picture. Taking the expected V magnitude of the M2V star (V = 24.24) as an upper limit to the optical emission from the ROSAT source implies $F_X/F_{opt} \geq 10^4$. Comparing with the $F_X/F_{opt}$ distribution of bright ROSAT all-sky survey sources identified in SIMBAD (e.g. Motch et al. 1998) shows that all galactic or extragalactic classes of sources other than isolated neutron stars are probably ruled out (see also Fig. 3 in Schwope et al. 1999). In particular, the source is optically too faint to be identified with even extreme cases of cataclysmic variables or AGN.

This conclusion is independent of the HRI attitude correction since none of the other optical candidates studied in the large ROSAT survey error circle is a likely counterpart of the X-ray source. In particular, the extragalactic objects lack the broad emission lines usually seen in soft AGN (e.g. Greiner et al. 1996).

Assuming a neutron star radius of 10 km implies a source distance of 900 pc for full surface emission. However, this distance estimate is very sensitive to the actual energy distribution in the ROSAT band. For instance, Rajagopal & Romani (1996) have shown that blackbody fits to neutron star model atmospheres folded through the ROSAT PSPC tend to overestimate the effective temperature by a factor of up to 3 depending on chemical composition. Applying the maximum correction could bring the source to much closer distances ($d \sim 100$ pc).

The total galactic $N_H$ in the direction of RX J1605.3+3249 is 2.47 $10^{20}$ cm$^{-2}$ (Dickey & Lockman, 1990) about twice that derived from the blackbody fits to PSPC data (see Fig. 2). However, this difference may not be significant since similar to the effective temperature, the estimated photelectric absorption sensitively depends upon the assumed soft X-ray energy distribution.

We conclude that RX J1605.3+3249 exhibits all the features, soft thermal-like spectrum, high $F_X/F_{opt}$, expected from an isolated neutron star.

### *5.2. Accretion from the interstellar medium*

As for RX J0720.4-3125, the average particle density available for accretion in the vicinity of the neutron star is probably small. IRAS maps do not reveal any particular density enhancement in the direction of RX J1605.3+3249. Using the mean particle density versus scale height law of Dickey & Lockman (1990) yields average densities of only 0.3 cm$^{-3}$ at 100 pc and 0.06 cm$^{-3}$ at 300 pc. In order to explain the X-ray luminosity of the source by Bondi Hoyle accretion, very low values of the total relative plus sound speed velocities must be achieved, 12 km s$^{-1}$ and 3.5 km s$^{-1}$ for $d$ = 100 and 300 pc respectively. In particular, large distances of the order of 900 pc as suggested by PSPC spectral fitting seem incompatible with the accretion model. However, this major difficulty could be bypassed assuming the presence of a local overdensity or if the blackbody modelling strongly overestimates the total accretion luminosity.

So far, three isolated neutron star candidates have been detected in the galactic plane ($|b| \leq 20°$ (Haberl et al. 1998) and only two RX J1605.3+3249 and 1RXS J130848.6+212708 (Schwope et al. 1999) above the plane. RX J1605.3+3249 is the X-ray brightest high galactic latitude candidate. The steep decrease of particle density with distance for RX J1605.3+3249 could allow to sensitively test the mechanism leading to X-ray emission in this newly discovered class of objects.

### *5.3. Cooling neutron star*

The strongest argument in favour of a young cooling neutron star is probably the stability of X-ray emission over long time scales. This property of RX J1605.3+3249 is also shared by RX J0720.4-3125 and RX J1856.5-3754. Neutron stars accreting in binaries always exhibit some kind of variability on a large range of time scales from seconds to months. Although the accretion conditions prevailing in binaries are usually far from those assumed for accretion from interstellar medium, it is still puzzling that none of the members of this new class so far studied in details shows convincing evidences for variability.

For normal pulsars, the blackbody temperature of 1.1 $10^6$ K implies cooling ages in the range of $2\times 10^4$ to $10^5$ yr depending on the presence of accreted material at the surface of the neutron star (Chabrier et al. 1997). Considering the probable overestimation of $T_{\rm eff}$ by the blackbody fit, ages of up to $10^6$ yr are still possible.

RX J1605.3+3249 and its cousins RX J0720.4-3125 and RX J1856.5-3754 have in common two properties which are never encountered together in other classes of neutron stars, i) absence of strong radio emission and ii) absence of luminous hard X-ray tail above the thermal spectrum. These features could be used to define the new class of objects.

Simultaneous absence of radio and hard X-ray emission is understandable in the framework of old accreting neutron stars. The low magnetic field or the long spin period necessary for accretion to take place are likely to put the pulsar beyond the death line, in the graveyard, and the emitted X-ray spectrum is expected to resemble that of a soft black body for a large range of parameters (Zampieri et al. 1995). We envisage below the implications of such properties for young cooling INS.

#### 5.3.1. Radio emission

The most simple explanation for the absence of radio emission is that the radio beam does not cross the earth. The beaming fraction which is the proportion of the sky swept by the radio beam decreases with increasing spin period (Biggs 1990) and is of the order of 0.2 for the overall pulsar population (e.g. Lyne et al. 1998). Therefore, radio detection means may miss a large fraction of the pulsar population among which a part may be hot enough to be detected in soft X-rays.

As noted by Kulkarni & van Kerkwijk (1998), this explanation cannot hold for the pulsating source RX J0720.4-3125 because the time needed to brake the neutron star to the long spin period of 8.39 s (assuming a magnetic field of $10^{12}$ G) is much larger than the cooling time. For the same reason, the absence of radio emission from RX J1605.3+3249 is unlikely to be due to a position beyond the death line as this would also imply rather long spin periods incompatible with the hot emission.

Another possibility is that RX J1605.3+3249 is a magnetar with a dipolar surface field B larger than about $4 \times 10^{13}$ G in which case radio emission may be quenched (Heyl & Kulkarni 1998).

#### 5.3.2. X-ray spectrum

The fact that the X-ray spectrum is to the accuracy of the measurements thermal-like suggests a much reduced magnetospheric activity compared to other known neutron stars.

Among the 27 pulsars detected in X-rays and listed in Becker & Trümper (1997), only three middle aged pulsars (Geminga, PSR B0656+14 and PSR B1055-52) have in addition to a power law a recognizable black body component in their soft X-ray energy distribution. An interesting case is PSR B0656+14, a radio emitting pulsar about $\sim 10^5$ yr old with a magnetic field of $4.7 \times 10^{12}$ G and located at a distance of 760 pc. PSR B0656+14 exhibits a ROSAT PSPC spectrum ($T_{\rm bb}$ = 80-90 eV; Possenti et al. 1996) strikingly similar to that of RX J1605.3+3249. The additional faint hard component needed to fit the spectrum of PSR B0656+14 would not have been detected in RX J1605.3+3249 because of the lower statistics.

Neutron stars born with magnetic field B $\geq 10^{14}$ G, the magnetars, are thought to be powerful soft X-ray emitters because magnetic field decay provides an additional source of heat (Thompson & Duncan 1996, Heyl & Kulkarni 1998). The young magnetars associated with soft $\gamma$-ray repeaters such as SGR 1806-20 or SGR 1900+14 exhibit powerlaw-like quiescent X-ray spectra without evidences for black body components. These non-thermal energy distributions could be the signature of a compact synchrotron nebula (Marsden et al. 1998). It has been proposed that the class of anomalous braking X-ray pulsars could be related to magnetars (e.g. Thompson & Duncan 1996) and could constitute a later, less active soft $\gamma$-ray repeater phase. In general, anomalous X-ray pulsars have again powerlaw-like spectra with in two cases possible blackbody components (see Thompson & Duncan 1996 and references therein). Pulsating sources like RX J0720.4-3125 could represent an even later stage of magnetar evolution with remaining very high magnetic field (B $\sim 10^{14}$ G, Heyl & Hernquist 1998) and perhaps still the possibility to emit powerful $\gamma$-ray bursts on occasion. Because of the additional energy source a magnetar could reach the temperature of 1.1 $10^6$ K after $10^6$ yr (Heyl & Hernquist 1998). It is however unclear whether the absence of a strong non-thermal component in the X-ray spectrum is compatible with the remaining high magnetic field.

### *5.4. Expected brightness of the optical counterpart*

Taking into account the unfortunate possibility of a chance alignement between the neutron star and object C implies a B magnitude fainter than $\sim$ 26 for RX J1605.3+3249. Because of the relatively high temperature, the extrapolation of the black body seen in soft X-rays to the optical regime would imply extremely faint optical magnitudes close to V = 30. However, all neutron stars observed so far display optical continuum above the Rayleigh-Jeans tail of the soft X-ray thermal component. This is not unexpected since black body fits tend to overestimate $T_{\rm eff}$ . Furthermore, a non thermal optical component has been detected in at least two cases, Geminga and PSR B0656+14. Scaling the optical flux with the PSPC count rate of RX J0720.4-3125 and RX J1856.5-3754 and neglecting any temperature effects yields V$\sim$27.2 for RX J1605.3+3249. On the other hand, if RX J1605.3+3249 is similar to Geminga or PSR B0656+14 its B magnitude could be as bright as our limit of 26. Therefore the source may well be bright enough to be optically identified with current means and optical imaging could allow the detection of proper motion which is a crucial test for determining the X-ray powering mechanism.

## 6. Conclusions

The only optical object detected in the small HRI error circle is a late M star most probably unrelated to the X-ray source. Altogether, X-ray and optical observations of RX J1605.3+3249 strongly suggest that the soft X-ray source is due to thermal emission from a nearby isolated neutron star. However, based on the presently available data, it is not possible to distinguish between accretion from the interstellar medium or cooling as the main X-ray emitting mechanism.

The constancy of the X-ray flux on various time scales and the difficulties encountered by the accretion model as a result of the small mean ambient densities are arguments, although not fully compelling, for a cooling neutron star.

The undetermined neutron star spin period and the lack of sensitive measurement of a hard X-ray component prevent us from drawing any firm conclusion on the nature of the source. One possibility is that RX J1605.3+3249 is a twin of PSR B0656+14 but that the radio beam does not intercept the earth. Alternatively, RX J1605.3+3249 could be a magnetar, maybe similar to RX J0720.4-3125.

Further sensitive optical and X-ray observations with the XMM and AXAF satellites could help to unveil the real nature of this object.

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

## References

Becker W., Trümper J., 1997, A&A 326, 682
Biggs J.D., 1990, MNRAS 245, 514
Blaes O., Madau P., 1993, ApJ 403, 690
Chabrier G., Potekhin A.Y., Yakovlev D., 1997, ApJ 477, L99
Christian C.A., Adams M., Barnes J.V., et al., 1985, PASP 97, 363
Danner R., 1998, A&AS 128, 331
Dickey J., Lockman F., 1990, ARA&A 28, 215
Duncan R.C., Thompson C., 1992, ApJ 392, L9
Greiner J., Danner R., Bade N., et al., 1996, A&A 310, 384
Haberl F., Motch C., Buckley D.A.H., Zickgraf F.-J., Pietsch W., 1997, A&A 326, 662
Haberl F., Motch C., Pietsch W., 1998, Astronomische Nachr. 319, 97
Hasinger G., Burg R., Giacconi R., et al., 1998, A&A 329, 482
Heyl J.S., Hernquist L., 1998, preprint
Heyl J.S., Kulkarni S.R., 1998, ApJ 506, L61
Jacoby G.H., Hunter D.A., Christian C.A., 1984, ApJS 56, 257
Kouveliotou C., Fishman G.J., Meegan C.A., et al., 1994, Nat 368, 125
Kouveliotou C., Dieters S., Strohmayer T., et al., 1998, Nat 393, 235
Kulkarni S.R., van Kerkwijk M.H., 1998, ApJ 507, L49
Lyne A.G., Manchester R.N., Lorimer D.R., et al., 1998, MNRAS 295, 743
Madau P., Blaes O., 1994, ApJ 423, 748
Manning R.A., Jeffries R.D., Willmore A.P., 1996, MNRAS 278, 577
Marsden D., Rothschild R.E., Kouveliotou C., Dieters S., van Paradijs J., 1998, To appear in the proceedings of the conference: Neutron Stars and Pulars - Thirty years after the Discovery. Held Novermber 17–20, 1997 in Tokyo
Motch C., Guillout P., Haberl, et al., 1997, A&A 318, 111
Motch C., Haberl F., 1998, A&A 333, L59
Motch C., Guillout P., Haberl F., et al., 1998, A&AS 132, 341
Ostricker J., Rees M.J., Silk J., 1970, Astrophys. Lett. 6, 179
Possenti A., Mereghetti S., Colpi M., 1996, A&A 313, 565
Rajagopal M., Romani R., 1996, ApJ 461, 327
Robin A., Creze M., 1986, A&A 157, 71
Schwope A.D., Hasinger G., Schwarz R., Haberl F., Schmidt M., 1999, A&A 341, L51
Thompson C., Duncan R.C., 1996, ApJ 473, 322
Torres-Dodgen A.V., Weaver W.B., 1993, PASP 105, 693
Treves A., Colpi M., 1991, A&A 241, 107
Wang J.C.L., 1999, A&A 345, 869
Walter F.M., Wolk S.J., Neuhäuser R., 1996, Nat 379, 233
Walter F.M., Matthews L.D., Lattimer P.A.J., Prakash M., Neuhäuser R., 1997, Proceedings of the 1997 HEAD meeting, Nov 4–7 1997, in press
Werner K., Dreizler S., Heber U., et al., 1996, A&A 307, 860
Zampieri L., Turolla R., Zane S., Treves A., 1995, ApJ 439, 849