The Magnificent Seven: Nearby Isolated Neutron Stars with strong Magnetic Fields

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1. Introduction

Estimates from the current pulsar birth rate and the number of supernovae to account for the heavy-element abundance suggest that in total $10^8$ to $10^9$ isolated neutron stars exist in our Galaxy. Only a small fraction is detectable as young neutron stars due to their emission of thermal X-rays (for $\sim 10^6$ years) or pulsed radio emission (for $\sim 10^8$ years). Proposals that an old "recycled" population of isolated neutron stars re-heated by accretion from the interstellar medium (ISM) should be detectable by ROSAT, triggered several projects to search for such objects in the ROSAT all-sky survey data. Over the last decade seven very soft X-ray sources with particular characteristics were discovered in ROSAT data. Extreme X-ray to optical flux ratios and low absorption column densities strongly suggest that these objects are nearby isolated neutron stars (see reviews by Treves et al. 2000; Motch 2001; Haberl 2004). Using HST, parallax measurements yield a distance of $117\pm12$ pc for RX J1856.5$-3754$ (Walter & Lattimer 2002). The detection of relatively high proper motion (PM) for the three brightest stars makes accretion from the ISM highly ineffective and favours the picture of cooling neutron stars with an age of $\sim 10^5$–$10^6$ years to power the X-rays. Tracing back the apparent trajectories suggests that the brightest of the ROSAT-discovered isolated neutron stars were born in the Sco OB2 complex which is the closest OB association (see e.g. Motch et al. 2005 and references therein).

The X-ray spectra of the "magnificent seven", as they are sometimes called in the literature, are thermal and blackbody-like without a hard power-law tail as it is often observed in other isolated neutron stars (e.g. Pavlov et al. 2002). Typical observed blackbody temperatures $kT$ are in the range of 40–110 eV (see Table 1). From five stars X-ray pulsations were detected with pulse periods between 3 s and 12 s and pulsed fractions between 4% and 18% (Fig. 1). However, for the X-ray brightest star RXJ1856.5$-3754$ no pulsations with a stringent upper limit on periodic variation of 1.3% (2$\sigma$ confidence level in the 0.02 – 1000 s range) were found (Burwitz et al. 2003). A surprising discovery was that the X-ray spectrum and the pulsed fraction observed from RX J0720.4$-3125$ changes on a time-scale of years which may be caused by precession of the neutron star (de Vries et al. 2004).

2. Broad absorption lines

XMM-Newton observations of the thermal isolated neutron stars revealed deviations from the Planckian shape in the X-ray spectra obtained by the EPIC-pn and RGS instruments. Fig. 2 shows a comparison of the EPIC-pn spectra of the six best observed thermal isolated neutron stars fitted with an absorbed blackbody model. Large residuals are seen from RBS 1223 (Haberl et al. 2003), RX J0720.4$-3125$ (Haberl et al. 2004b) and RX J1605.3+3249, in the latter case the deviations were discovered in RGS spectra (van Kerkwijk et al. 2004). Non-magnetic neutron star atmosphere models (e.g. Gänside et al. 2002; Zavlin & Pavlov 2002) can not explain the X-ray spectra: Iron and solar mixture atmospheres cause too many absorption features and deviations from a blackbody model in particular at energies between 0.5 and 1.0 keV which are not seen in the measured spectra. On the other hand the spectrum of a pure hydrogen model is similar in shape to that of a blackbody and does not fit the data either. Moreover, hydrogen atmosphere models
Table 1. X-ray and optical properties of the magnificent seven

| Object              | kT  | Period | Amplitude | Optical | PM    | Ref. |
|---------------------|-----|--------|-----------|---------|-------|------|
| RX J0420.0−5022     | 44  | 3.45   | 13        | B = 26.6|       | 1    |
| RX J0720.4−3125     | 85-95 | 8.39 | 8-15      | B = 26.6| 97    | 2,3,4,5,6 |
| RX J0806.4−4123     | 96  | 11.37  | 6         | B > 24  |       | 7.1  |
| RBS 1223(1)         | 86  | 10.31  | 18        | m bó = 28.6| 8,9,10,11 |
| RX J1605.3+3249     | 96  | −      | −         | V = 25.7| 332   | 16,17,18 |
| RX J1856.5−3754     | 60  | −      | <1.3      | R > 23  |       | 19,20 |
| RBS 1774(2)         | 101 | 9.44   | 4         |         |       |      |

References: (1) Haberl et al. (2004a) (2) Haberl et al. (2003,7+065419) (3) Cropper et al. (2001) (4) Haberl et al. (2004b) (5) de Vries et al. (2004) (6) Motch et al. (2003) (7) Haberl & Zavlin (2002) (8) Schwone et al. (1999) (9) Hambaryan et al. (2002) (10) Kaplan et al. (2002) (11) Haberl et al. (2003) (12) Motch et al. (1999) (13) Kaplan et al. (2003) (14) van Kerkwijk et al. (2004) (15) Motch et al. (2003) (16) Walter & Matthews (1997) (17) Walter & Lattimer (2002) (18) Burwitz et al. (2003) (19) Zampieri et al. (2001) (20) Zane et al. (2005)

Table 2. Magnetic field estimates

| Object              | dP/dt | E_cyc | B_db | B_cyc |
|---------------------|-------|-------|------|-------|
| RX J0420.0−5022     | <92   | 330?  | <18  | 6.6?  |
| RX J0720.4−3125     | 1.4±0.6 | 260 | 2.8−4.2 | 5.2      |
| RX J0806.4−4123     | <18   |       |      | <14   |
| RBS 1223            | <9    | 100-300| <10  | 2−6   |
| RX J1605.3+3249     | 450-480| ~1   |      | 9.1−9.7 |
| RX J1856.5−3754     | ~700  | ~14  |      |       |

over-predict the actually observed optical fluxes by large factors (~300, see Zavlin & Pavlov 2002).

The XMM-Newton spectra can best be modeled with a Planck continuum including a broad, Gaussian shaped absorption line (Fig. 3). Line centroid energies are summarized in Table 2. In the EPIC-pn data of RBS 1223 (see also Schwone et al. 2005) and RX J0720.4−3125 the depth of the absorption line (or the equivalent width) was found to vary with pulse phase. In the cases of RX J0806.4−4123 and RX J0420.0−5022 it is not clear to which extent the residuals of the blackbody fits are caused by systematic calibration uncertainties (Haberl et al. 2004a). In particular RX J0806.4−4123 shows a residual pattern similar to that of RX J1856.5−3754 which is believed to exhibit a pure blackbody spectrum as seen from the high resolution Chandra LETGS spectrum (Burwitz et al. 2003). For RBS 1774 recently an absorption feature at ~0.7 keV was reported from the analysis of EPIC spectra (Zane et al. 2003). At such high energies (the highest line energy reported from the thermal isolated neutron stars) the energy resolution is better and the calibration uncertainties smaller than at lower energies.

3. Strongly magnetized neutron stars

An H$_\alpha$ emission line nebula was discovered around RX J1856.5−3754 (van Kerkwijk & Kulkarni 2001). Assuming that magnetic dipole breaking powers this nebula and using an age of the star of 5 x 10$^5$ years (Walter & Lattimer 2002) allows an estimate of the magnetic field strength of the neutron star of B $\sim$ 10$^{13}$ G (Braje & Romani 2002; Trümper 2003). A similar magnetic field strength of (2.8−4.2) x 10$^{13}$ G was inferred from the pulse period history of RX J0720.4−3125 as observed with ROSAT, Chandra and XMM-Newton over a time span of 10 years (Cropper et al. 2004).
These were the first indications that the group of thermal isolated neutron stars possess strong magnetic fields of the order of $10^{13} - 10^{14}$ G. Such strong fields are indeed required to spin down the neutron stars to their current long rotation periods within $10^5 - 10^6$ years (still being sufficiently hot to be detected in X-rays) if they were born with msec periods.

Cyclotron resonance absorption features in the 0.1–1.0 keV band are expected in X-ray spectra from magnetized neutron stars with field strengths in the range of $10^{10} - 10^{11}$ G or $2 \times 10^{13} - 2 \times 10^{14}$ G if caused by electrons or protons, respectively (see e.g. Zane et al. 2001; Zavlin & Pavlov 2002). Variation of the magnetic field strength over the neutron star surface (as expected for dipole fields) leads to a broadening of the line (Ho & Lai 2004). The strong magnetic fields inferred from magnetic dipole breaking effects in at least two of the stars suggests that the broad absorption features seen in the X-ray spectra of thermal isolated neutron stars originate from cyclotron resonance absorption by protons or highly ionized atoms of heavy elements. With a mass to charge ratio of $\sim 2$ with respect to protons the latter case would lead to B a factor of $\sim 2$ higher than that derived for protons. Different ionization states would result in a series of lines with energies differing by only a few percent, leading to additional broadening of the lines.

An alternative possibility for the origin of the absorption line is atomic bound-bound transitions. In strong magnetic fields atomic orbitals are distorted into a cylindrical shape and the electron energy levels are similar to Landau states, with binding energies of atoms significantly increased. E.g. for hydrogen in a mag-
Fig. 2. EPIC-pn and RGS spectra of thermal isolated neutron stars fitted with an absorbed black-body model. The fits represent the calibration status as available with SAS release 6.0.0.

A magnetic field of the order of $10^{13}$ G the strongest atomic transition is expected at energy $E/eV \approx 75(1+0.13\ln(B_{13}))+63B_{13}$, with $B_{13} = B/10^{13}$ G (Zavlin & Pavlov 2002). For the line energies found in the spectra of thermal isolated neutron stars this would require similar field strengths to those derived assuming cyclotron absorption. Atomic line transitions are expected to be less prominent at higher temperatures because of a higher ionization degree (Zavlin & Pavlov 2002).

4. Conclusions

Although the true origin of the broad absorption lines in X-ray spectra of thermal isolated neutron stars is not clear yet, our current knowledge about the “magnificent seven” strongly suggests
that they are highly magnetized (10^{13} - 10^{14} G), slowly rotating cooling neutron stars. Further timing studies would be very useful to obtain more independent estimates of the magnetic field strength (as they currently only exist from RX J0720.4−3125).

We do not detect radio emission, probably because their radio beam is very narrow due to their large light cylinder radius. The discovery of a few radio pulsars with similar magnetic field strength and long period ([Camilo et al.] 2000; [Morris et al.] 2002; [McLaughlin et al.] 2003) shows that radio emission can still occur at inferred field strengths higher than the “quantum critical field” \( B_{cr} = \frac{m_e^2 c^3}{\hbar e} \approx 4.4 \times 10^{13} \) G. On the other hand, any non-thermal emission from the “magnificent seven” may so far just fall below the detection threshold of current instruments ([Zane et al.] 2003).

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Fig. 3. Top two panels: EPIC-pn and RGS spectra of two thermal isolated neutron stars fitted with an absorbed blackbody model including a broad absorption line. Bottom panel: RGS spectrum of RX J1605.3+3249 modeled with blackbody continuum and broad absorption line. A possible additional narrow absorption line at 21.5Å is also included (from [van Kerkwik et al.] 2004).
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