The thermal radiation of the isolated neutron star
RX J1856.5–3754 observed with Chandra and XMM-Newton

V. Burwitz, F. Haberl, R. Neuhäuser, P. Predehl, J. Trümper, and V. E. Zavlin

Max-Planck-Institut für extraterrestrische Physik, P.O. Box 1312, D-85741 Garching, Germany

Received October 24, 2002; accepted November 25, 2002

Abstract. We present results of the analysis of data collected in 57-ks XMM-Newton and 505-ks Chandra observations of the nearby (~120 pc) isolated neutron star RX J1856.5–3754. We confirm most of the statements made by Burwitz et al. (2001) who discussed the original 55-ks Chandra data. Detailed spectral analysis of the combined X-ray and optical data rules out the currently available nonmagnetic light and heavy element neutron star atmosphere (LTE) models with hydrogen, helium, iron and solar compositions. We find that strongly magnetized atmosphere models also are unable to represent the data. The X-ray and optical data show no spectral features and are best fitted with a two-component blackbody model with \( kT_{\text{bb}} \approx 63.5 \text{ eV} \) and \( R_{\text{bb}} \approx 4.4 \, \text{(d/120 pc)} \) km for the hot X-ray emitting region, and \( kT_{\text{opt}} \approx 33 \text{ eV} \) and \( R_{\text{opt}} \approx 17 \, \text{(d/120 pc)} \) km for the rest of the neutron star surface responsible for the optical flux. The large number of counts collected with XMM-Neutron allows us to reduce the upper limit on periodic variation in the X-ray range down to 1.3% (at a 2σ confidence level) in the \( 10^{-3} - 50 \) Hz frequency range. In an attempt to explain this small variability, we discuss an one-component model with \( kT_{\text{bb}} \approx 63 \text{ eV} \) and \( R_{\text{bb}} \approx 12.3 \, \text{(d/120 pc)} \) km. This model requires a low radiative efficiency in the X-ray domain, which may be expected if the neutron star has a condensed matter surface.

Key words. stars: atmospheres – stars: individual: RX J1856.5–3754 – stars: neutron – X-rays: stars

1. Introduction

1.1. Thermal radiation from isolated neutron stars

Thermal emission from the surface of an isolated neutron star (NS) could be very useful for determining the star’s mass \( M \) and the radius \( R \), what in turn puts important contraints on the equation of state of matter at supranuclear densities.

Specifically, the detection of spectral features in radiation of isolated NSs may provide:

\begin{itemize}
  \item chemical composition of the NS surface,
  \item the surface gravity from the line broadening,
  \item the mass-to-radius ratio from measurement of gravitational redshift of the lines,
  \item strength of the surface magnetic field.
\end{itemize}

ROSAT was the first satellite with a sufficient sensitivity in the soft X-ray band (0.1 – 2.0 keV) to start a systematic search and study of isolated NSs which reveal blackbody-like thermal emission. Seven such objects emitting soft thermal X-ray spectra, having high X-ray/optical flux and invisible in radio band were detected with ROSAT (see, e. g., Zampieri et al. 2001 for the complete list).

Send offprint requests to: Vadim Burwitz, e-mail: burwitz@mpe.mpg.de

RX J1856.5–3754 (or RXJ1856 throughout the text) is the brightest of them in X-rays.

We use apparent temperatures \( T_{\text{bb}} \) and radii \( R_{\text{bb}} \) which are measured by a distant observer, throughout this paper. The true parameters as measured at the neutron star surface are given by \( T_{\text{bb}} = T_{\text{bb}}^\infty (1 - r_g/R)^{-1/2} \) and \( R_{\text{bb}} = R_{\text{bb}}^\infty (1 - r_g/R)^{1/2} \) where \( r_g = 2GM/c^2 \) is the Schwarzschild radius of the NS.

1.2. Previous Observations

Walter et al. (1996) and Neuhäuser et al. (1997) first concluded that RXJ1856 is an isolated NS. The ROSAT data showed that RXJ1856 has a non-variable X-ray flux of \( \approx 1.5 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} \) and a soft spectrum with a blackbody temperature of \( kT_{\text{bb}}^\infty \approx 57 \text{ eV} \). Very interestingly, the Planckian shape of the spectrum was confirmed later with the first high-resolution Chandra LETGS data (Burwitz et al. 2001 hereafter B01). Actually, the grating spectrum did not show any significant deviations from a Planckian, which are expected in spectra of NS atmospheres containing heavy chemical elements.

The faint optical counterpart with \( V \approx 26 \text{ mag} \) of RXJ1856 was discovered by Walter & Matthews (1997) and confirmed by Neuhäuser et al. (1998). Walter (2001) and Neuhäuser (2001) used the faintness of the opti-
Table 1. Journal of Chandra and XMM-Newton observations

| Obs. Id. | Instrument (mode) | Obs. Start [UT] | Obs. End [UT] | Exposure [ksec] | Type | Remark |
|---------|------------------|-----------------|--------------|-----------------|------|--------|
| Chandra |
| 113     | LETGS            | 2000/03/10      | 2000/03/10   | 55.48           | GTO  |        |
| 3382    | LETGS            | 2001/10/08      | 2001/10/09   | 101.96          | DDT  |        |
| 3380    | LETGS            | 2001/10/10      | 2001/10/12   | 167.50          | DDT  |        |
| 3381    | LETGS            | 2001/10/12      | 2001/10/14   | 171.13          | DDT  |        |
| 3399    | LETGS            | 2001/10/15      | 2001/10/15   | 9.32            | DDT  |        |
| XMM-Newton |
| 0106260101 EPIC-pn (SW) | 2002/04/08      | 2002/04/09   | 57.193          | GTO  | effective exposure~71% = 40 ks |
| 0106260101 EPIC-MOS1 (TT) | 2002/04/08      | 2002/04/09   | 57.740          | GTO  | no response available yet |
| 0106260101 EPIC-MOS2 (SW) | 2002/04/08      | 2002/04/09   | 57.996          | GTO  |        |
| 0106260101 RGS1 | 2002/04/08     | 2002/04/09   | 58.546          | GTO  |        |
| 0106260101 RGS2 | 2002/04/08     | 2002/04/09   | 58.546          | GTO  |        |

None of the previous analysis of the X-ray data yielded any significant periodicity. With the ROSAT data Pons et al. (2002) derived an upper limit of 6% on the rotational modulation of the flux for periods in the range 0.1 s – 20 s. B01, using the data from the first 55-ks Chandra observation of RXJ1856, put a limit of 8% in the period range 25 ms – 10 s. B01 found that the RXJ1856 spectrum detected with the Chandra LETGS instrument in the 55-ks observation is best fitted to a blackbody model with $kT_{bb,X} = (63.0 \pm 1.0)$ eV and $R_{bb,X} = 4.4 \pm 0.5$ km ($d/120$ pc). A fit to the 505-ks LETGS spectrum yields very similar, but much more constrained values of $kT_{bb,X} = 63.5 \pm 0.2$ eV and $R_{bb,X} = 4.4 \pm 0.1$ km ($d/120$ pc). The fit is shown in Fig. 2 (right panels).

The results of individual fits with blackbody model to the spectra from different instruments are given in Fig. 1 and Table 2. The Chandra and XMM-Newton data yield temperatures well consistent with each other and significantly different from that obtained with the ROSAT PSPC. The differences in the inferred values of model parameters are attributed to systematic uncertainties in the present calibrations of the X-ray instruments.

4. Timing analysis
Details on results from the timing analysis of the Chandra data can be found in B01, Ransom, Gaensler, & Slane (2002) and Drake et al. (2002). The 57-ks observation with the
Fig. 1. The top panel shows the countrate spectra of RXJ1856 obtained with XMM-Newton and Chandra with the best single blackbody model fit to each instrument (the parameters are given in Table 2). The bottom two panels show the ratio between the data and the model for both the CCD detectors and the high resolution grating instruments.

Table 2. Results of spectral fits to the X-ray data.

| Mission       | Instrument | $n_H$ $10^{20} \text{ cm}^{-2}$ | $kT_{bb} \text{ eV}$ | $R_{bb}^2 \text{ km (d/120 pc)}$ | $f_X (0.1 - 1.0 \text{ keV}) 10^{-11} \text{ erg/cm}^2/\text{s}$ | $L_{bol} 10^{37} \text{ erg/s}$ | $\chi^2 / \text{ d.o.f.}$ |
|---------------|------------|-------------------------------|---------------------|---------------------------------|-------------------------------------------------|-----------------|-----------------|
| ROSAT         | PSPC       | 1.46±0.20                     | 56.7±1.0            | 7.5±0.5                         | 1.45                                            | 7.5             | 0.9/16          |
| Chandra       | LETGS      | 0.95±0.03                     | 63.5±0.2            | 4.4±0.1                         | 1.14                                            | 4.1             | 1.2/1145        |
| XMM-Newton    | EPIC-pn    | 0.18±0.03                     | 62.8±0.3            | 4.3±0.1                         | 1.67                                            | 3.7             | 2.3/122         |
| XMM-Newton    | EPIC-MOS2  | 0.67±0.02                     | 62.6±0.4            | 4.4±0.1                         | 1.32                                            | 3.8             | 6.1/41          |
| XMM-Newton    | RGS1+RGS2  | 0.87±0.08                     | 63.4±0.3            | 4.0±0.2                         | 0.90                                            | 3.3             | 1.1/717         |

the XMM-Newton EPIC-pn instrument provided much larger statistics (370,230 counts extracted from a 30” radius circle centered at the source position) at a 6-ms time resolution. The standard $Z^2_1$-test (Buccheri et al. 1983) run in the $10^{-3} - 50$ Hz frequency range revealed a maximum value $Z^2_{1\text{,max}} = 33.3$, that translates into an upper limit of 1.3% (at a 2σ confidence level) on variability of the detected radiation assuming a sine-like signal.

5. Discussion

Pavlov et al. (1996) and Pons et al. (2002) showed that the light element (hydrogen and helium) nonmagnetic NS atmosphere models can be firmly ruled out because they, applied to the X-ray data on RXJ1856, yield (i) too small distance estimates ($d < 10$ pc) and (ii) overpredict the optical flux measured from the source by a factor of ∼ 100. As first demonstrated by B01, no acceptable fit can be obtained with iron and standard solar-mixture atmosphere models (see Zavlin & Pavlov 2002 for a recent review on the NS atmosphere modeling) at any reasonable values of gravitational redshift parameter (see B01 for a more
detailed discussion). In case of the solar-mixture composition, the X-ray data rule out the models with heavy element abundances greater than 0.05%. Fig. 2 (left panels) shows an example of a spectral fit with a NS atmosphere model where heavy elements provide only 0.2% of the total mass density.

As shown in Zavlin & Pavlov (2002), sharp features in the spectra of NS heavy-element atmospheres, primarily spectral lines, may be smeared out by a fast NS rotation at periods as short as a few milliseconds. However, this rotational broadening (the Doppler effect) of the spectral features yet leaves broad-band spectral features in the model spectra at energies around most prominent absorption edges, that make these atmosphere models fail to fit the X-ray data (Pavlov, Zavlin & Sanwal 2002; Braje & Romani 2002).

Another possibility would be to fit the data with NS atmosphere models for strong magnetic fields. However, available magnetized hydrogen models, although not well elaborated yet for such rather low temperatures of interest (see Zavlin & Pavlov 2002 for discussion), have the same problem as the nonmagnetic case: they overpredict the optical flux. On the other hand, the spectra emitted by magnetized iron atmospheres (Rajagopal, Romani & Miller 1997) show numerous absorption features which should be detectable with the modern instruments of high energy resolution. We note that smearing of spectral features due to line shifts in inhomogeneous magnetic fields (for example, varying by a factor of 2 over the NS surface for a dipole magnetic field configuration) may be expected to wash away narrow-band features, but anyway, should result in broad-band deviations from the blackbody spectrum, similar to the case of a fast rotating NS, as discussed above.

We conclude that the “classic” NS atmosphere models (with assumption of radiative equilibrium) are unable to reproduce the X-ray emission of RXJ1856, which is best fitted by a simple blackbody model (see Fig. 2, right panels). The possibility of a NS atmosphere which is not in radiative equilibrium since its outer layers heated by particle or photon irradiation has been discussed by Gänsicke, Braje & Romani (2002). In this case one can produce a
spectrum which is close to that of a blackbody. However, this remains a pure speculation until the required source of the additional heating is identified.

An alternative possibility is to assume a condensed matter surface — liquid or solid — which might result in a virtually featureless Planckian spectrum in the soft X-ray band. Such a situation may occur at low temperatures \( kT < 86 \text{ eV} \) and high magnetic fields \( (B > 10^{13} \text{ G}) \) when hydrogen, if present on the NS surface, is expected to be in the form of polyatomic molecules (Lai & Salpeter 1997; Lai 2001).

Yet another problem arises from the fact that the parameters derived from X-rays \( (kT_{\text{bb},X} = 63 \text{ eV} \) and \( R_{\text{bb},X} = 4.4 \text{ (d/120 pc) km}) \) do not fit the optical data obeying the Rayleigh-Jeans law with an intensity about a factor of 7 larger than that given by the continuation of the blackbody model yielded by the X-ray data. This situation has led Pons et al. (2002) to introduce a two-component interpretation: the model applied in the X-ray band is supplemented with an additional soft blackbody component emitted from about 80% of the NS surface and being responsible for the optical emission (c.f. Fig. 3 left). The requirement that the soft component does not contribute in the X-ray band puts an upper limit on the blackbody temperature \( kT_{\text{bb,opt}} < 33.6 \text{ eV} \) (a 3σ confidence level), that restricts the stellar radius \( R_{\text{bb,opt}} > 16.3 \text{ (d/120 pc) km} \) (Pavlov, Zavlin & Sanwal 2002). We also note that the spectral shape of the optical blackbody data puts a lower limit on the temperature of the soft component \( kT_{\text{bb,opt}} \geq 4 \text{ eV} \) and an upper limit on its radius \( R_{\text{bb,opt}} \leq 46 \text{ (d/120 pc) km} \).

The non-observed modulation of the X-ray flux imposes severe restrictions on the viewing geometry which has been discussed quantitatively by Braje & Romani (2002). Using the previous limits on the pulsed fraction (<4%) they found “the fraction of the sky allowed by pulsed fraction constraints” (which translates into a probability of a given orientation of the rotational and viewing axes) of 2-4% for a NS radius of \( \sim 16 \text{ km} \). The new limit established with \textit{XMM-Newton} on the pulsed fraction reduces the allowed sky fraction to even smaller values (around 1%). Alternatively, RXJ1856 could rotate with a short period of a few milliseconds (the available X-ray data do not provide sufficient time resolution for searching periodic signals at these time scales). But this seems unlikely in view of the NS age of \( \sim 0.5 \text{ Myr} \) implied by its rather low surface temperature and the inferred distance from its birth place (Walter & Lattimer 2002).

6. Alternative models

The absence of periodic variations and spectral features in the observed radiation imposes very stringent constraints on any model. The simplest way to produce a time con-
stant flux would be to assume a uniform temperature distribution across the stellar surface. For a temperature of $kT_{bb} = 63 \text{ eV}$ the measured optical spectrum requires a blackbody radius $R_{bb}^\infty \simeq 12.3 \text{ km}$. Consequently, the X-ray emissivity has to be below that of a blackbody by a substantial factor. Using the parameters derived from the Chandra data (c.f. Fig. 3 right) we find this factor to be about 0.15 (it can be about 0.45 if one adopts the parameters given by the ROSAT data). This would mean that the emitting surface should have a high reflectivity as may be expected for a condensed matter surface (Lenzen & Trümper 1978; Brinkmann 1980). In this case the spectrum may be represented by a $\alpha \propto B_0$ dependence ($B_0$ is the Planck function), where $\alpha$ is the absorption factor ($\sim [1 - \rho_X]$, with $\rho_X$ being the reflection factor), which in the general case will be energy-dependent (Brinkmann 1980). We have tested this hypothesis by fitting the Chandra LETGS spectrum with a Planckian $B_0$ multiplied by an energy dependent absorption factor $\alpha_X = E^\beta$ where $E$ is the photon energy. It turns out that the best fit yields $\beta = 1.28 \pm 0.30, kT_{bb} = 54 \pm 2 \text{ eV}$, and $n_H = (5.1 \pm 0.3) \times 10^{19} \text{ cm}^{-2}$. This indicates that at a 4$\sigma$ level we find find deviations from a Planckian spectrum which may result from an energy dependent absorption factor. In this case the radius required from the optical spectrum is $R_{bb}^\infty \simeq 13.3 \alpha_{opt}^{1/2} (d/120 \text{ pc}) \text{ km}$, where $\alpha_{opt} \lesssim 1$ is the absorption factor of the surface in the optical domain.

In conclusion, the two versions of our one-component model yield radii of $R^\infty = 12.3 \text{ km}$ and 13.3 km, respectively. These are lower limits as the absorption factor $\alpha$ may be smaller than unity in the optical band. We note that the observed radii correspond to true NS radii of $R > 9.1 \text{ km}$ and $R > 10.3 \text{ km}$ (for a NS mass of 1.4 $M_\odot$), respectively, which are consistent with a soft equation of state. But, of course, the possible range of parameters allows stiff equations of state as well.

Two main conditions have to be fulfilled to make this model work. Firstly, the NS has to have a condensed matter surface, which requires a low temperature and a strong magnetic field. The former seems to be fulfilled in this case: with a temperature of $kT = 54 - 63 \text{ eV}$ RXJ1856 is the coldest one of all detected isolated NSs. But its magnetic field is still unknown. The second condition is that the condensed matter surface really exhibits the required high reflectivity ($\sim 0.55 - 0.85$) in the X-ray domain. It remains to be seen whether a detailed analysis of the optical properties of magnetically condensed matter substantiates this hypothesis.

Note added in Proof: Turolla, Zane & Drake (2002) have submitted a paper to ApJ in which they treat the emissivity of a condensed matter surface from a theoretical point of view, using the method of Brinkmann (1980).

Acknowledgements. The XMM-Newton and the Chandra LETG projects are supported by the Bundesministerium für Bildung und Forschung/Deutsches Zentrum für Luft- und Raumfahrt (BMBF/DLR) and the Max-Planck Society. We would also like to thank the anonymous referee for constructive comments.

References

Braje, T. M., Romani, R. W., 2002, ApJ, in press (astro-ph/0208065)
Buccheri, R., Bennett, K., Bignami, G. F., et al., 1983, A&A 128, 245
Brinkman, W., 1980, A&A 82, 352
Burwitz, V., Zavlin, V. E., Neuhäuser, R., Predehl, P., Trümper, J. Brinkman, A. C., 2001, A&A 379, L35 [B01]
Drake, J. J., Marshall, H. L., Dreizler, S., Freeman, P. E., Fruscione, A., et al. 2002, ApJ 572, 996
Gänsicke, B. T., Braje, T. M., Romani, R. W., 2002, A&A 386, 1001
Kaplan, D. L., van Kerkwijk, M. H., Anderson, J. 2002, ApJ 571, 447
Lai, D., Salpeter, E. E., 1997, ApJ 491, 270
Lai, D., 2001, Rev. of Mod. Phys. 73, 629
Lenzen, R., Trümper, J., 1978, Nature 271, 216
Neuhäuser, R., Thomas, H.-C., Danner, R., Peschke, S., Walter, F. M., 1997, A&A 318, L43
Neuhäuser, R., Thomas, H.-C., Walter, F. M., 1998, The Messenger 92, 27
Neuhäuser, R., 2001, AN 322, 318563
Pavlov, G. G., Zavlin, V. E., Trümper, J., Neuhäuser, R., 1996, ApJ 472, L33
Pavlov, G. G., Zavlin, V. E., Sanwal, D., 2002, in Neutron Stars and Supernova Remnants, Eds. Becker, W., Lesch, H., Trümper, J., MPE Report 278, 273 (astro-ph/0206024)
Pons, J. A., Walter, F. M., Lattimer, J. M., Prakash, M., Neuhäuser, R., An, P., 2002, ApJ 564, 981
Rajagopal, M., Romani, R. W., Miller, M. C., 1997, ApJ 479, 347
Ransom, S. M., Gaensler, B. M., Slane, P. O. 2002, ApJ 570, L78
van Kerkwijk, M. H., Kulkarni, S. R. 2001, A&A 378, 986
Walter, F. M., Wolk, S. J., Neuhäuser, R., 1996, Nature 379, 233
Walter, F. M., Matthews, L. D., 1997, Nature 389, 358
Walter, F. M., 2001, ApJ 549, 433
Walter, F. M., Lattimer, J. 2002, ApJ 576, L145
Zampieri, L., Campana, S., Turolla, R., Chieregato, M., Falomo, R., et al. 2001, A&A 378, L5
Zavlin, V. E., Pavlov, G. G., 2002, in Neutron Stars and Supernova Remnants, Eds. Becker, W., Lesch, H., Trümper, J., MPE Report 278, p. 261 (astro-ph/0206025)