A time-variable, phase-dependent emission line in the X-ray spectrum of the isolated neutron star RX J0822−4300

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ABSTRACT
RX J0822−4300 is the central compact object associated with the Puppis A supernova remnant. Previous X-ray observations suggested RX J0822−4300 to be a young neutron star with a weak dipole field and a peculiar surface temperature distribution dominated by two antipodal spots with different temperatures and sizes. An emission line at 0.8 keV was also detected. We performed a very deep (130-ks) observation with XMM–Newton, which allowed us to study in detail the phase-resolved properties of RX J0822−4300. Our new data confirm the existence of a narrow spectral feature, best modelled as an emission line, only seen in the ‘soft’-phase interval – when the cooler region is best aligned to the line of sight. Surprisingly, comparison of our recent observations to the older ones yields evidence for a variation in the emission-line component, which can be modelled as a decrease in the central energy from \(\sim 0.80\) keV in 2001 to \(\sim 0.73\) keV in 2009–10. The line could be generated via cyclotron scattering of thermal photons in an optically-thin layer of gas, or, alternatively, it could originate in low-rate accretion by a debris disc. In any case, a variation in energy, pointing to a variation of the magnetic field in the line-emitting region, cannot be easily accounted for.

Key words: stars: neutron – pulsars: general – X-rays: individual: RX J0822−4300.

1 INTRODUCTION
Central compact objects (CCOs) in supernova remnants (SNRs) are a handful of about 10 point-like, thermally emitting X-ray sources located close to the geometrical centres of non-plerionic SNRs, with no counterparts at any other wavelength. CCOs are supposed to be young, isolated, radio-quiet neutron stars (see De Luca 2008, for a review).

While the first discovered CCO (the one in the RCW103 SNR) turned out to be a unique object (De Luca et al. 2006), results of X-ray timing on a subsample of sources with fast periodicities have recently set very useful constraints for a general picture of CCOs as a class. Analysis of multi-epoch XMM–Newton and Chandra observations of 1E 1207.4−5209 inside G296.5+10.0 and of CXOU J185238.6+004020 at the centre of Kes 79 (\(P = 424\) and 105 ms, respectively) yielded unambiguous evidence for very small period derivatives (Halpern & Gotthelf 2010, 2011). This implies, under standard rotating dipole assumptions, characteristic ages exceeding the age of the host SNRs by more than three orders of magnitude, as well as very small (\(\lesssim 10^{11}\) G) dipole magnetic fields. This points to an interpretation of such sources as ‘anti-magnetars’ – weakly magnetized isolated neutron stars – born with a spin period almost identical to the currently observed one.

Such a picture has recently been strengthened by the discovery of 112-ms pulsations from RX J0822−4300, the CCO in the Puppis A SNR (Gotthelf & Halpern 2009), in two archival XMM–Newton data sets collected in 2001, previously used by Hui & Becker (2006) for a comprehensive spectral analysis of the neutron star and of the surrounding SNR. Gotthelf, Perna & Halpern (2010), using a 2010
2 OBSERVATIONS AND DATA REDUCTION

Our study is based on a very deep (~130 ks) observation with XMM–Newton, originally scheduled to fit into a single satellite orbit (revolution number 1836), started on 2009 December 17. However, the launch of the Helios 2B spacecraft required support from XMM–Newton ground stations, which resulted in an ~50-ks data gap in the middle of the orbit. The observation was completed on 2010 April 5. We also included in our study the two archival, shorter data sets, obtained on 2001 April 15 (~29 ks) and 2001 November 8 (~24 ks), used by Gotthelf & Halpern (2009) in their previous investigations. A summary of the observations is reported in Table 1.

We focus on data obtained by the pn detector (Strüder et al. 2001) of the European Photon Imaging Camera (EPIC). The detector was operated in the small-window mode (time-resolution of 5.7 ms, field of view of 4.3 × 4.3 arcmin²). The thin optical filter was used in all observations. EPIC/pn observation data files were processed with the XMM–Newton SAS v11 (Science Analysis Software) using standard pipelines.

3 TIMING ANALYSIS

For our timing analysis, we selected the pn source events from a circular region of 30 arcsec radius, including only 1- and 2-pixel events (PATTERN 0 to 4) with the default flag mask. Photon arrival times were converted to the Solar system barycentre TBD time using the Chandra position (Gotthelf & Halpern 2009).

Before the analysis presented in Gotthelf & Halpern (2009), the pulsations in RX J0822–4300 eluded detection for many years, because of a phase shift of about half a cycle between the nearly sinusoidal profiles in the soft (<1.2 keV) and hard bands. By computing Z^2_i periodograms (Buccheri et al. 1983), we found that the energy bands that maximize the pulsed signal are 0.46–1.17 and 1.25–5.12 keV. The resulting soft and hard pulse profiles of the individual XMM–Newton observations (Table 1) were cross-correlated, shifted and summed to create two distinct pulse profile templates. Owing to the higher signal-to-noise ratio of the 1.25–5.12 keV profiles, we carried out the analysis in the hard band, but we checked that the results are fully consistent with those obtained in the soft band. The hard pulse profiles from temporal segments of the XMM–Newton observations were cross-correlated with the template to determine times of arrival at each epoch. By means of a phase-fitting analysis (e.g. Dall’Osso et al. 2003), we measured the periods given in Table 1 (we also confirm the measurements by Gotthelf & Halpern 2009 for observations A and B).

We attempted to obtain a full phase-connected timing solution (i.e. a solution that accounts for all the spin cycles of the pulsar) for the longest possible time. Unfortunately, it was not possible to univocally phase-connect the solution found for the two adjacent data sets C and D to other observations (the uncertainty on the phase – propagated along the large time-span to other observations – largely exceeds 1 cycle). A linear fit of the periods in Table 1 gives for the period derivative (9 ± 12) × 10^{-17} s^{-1}, which translates into 3σ limits −2.7 × 10^{-16} < Ṗ < 4.5 × 10^{-16} s^{-1} (in agreement with the limits recently published in Gotthelf et al. 2010). The period derivative at the Solar system barycentre results from the intrinsic pulsar spin-up/spin-down plus the contributions due to any external gravitational field and the pulsar proper motion (e.g. Phinney 1992). In the case of RX J0822–4300, for an assumed distance of 2.2 kpc (Reynoso et al. 1995), the Galactic contribution is negative and negligible (~−2 × 10^{-20} s^{-1}) and that produced by the proper motion (165 ± 25 mas yr^{-1}; Winkler & Petre 2007) is 1.6 × 10^{-16} s^{-1}. While the total (Galactic + proper motion) contribution does not impact significantly the current limits on the P of RX J0822–4300, we note that it is larger than the period derivative measured for the CCO in Kes 79 (~8.7 × 10^{-18} s^{-1}; Halpern & Gotthelf 2010).

The phase of the pulse peak is energy-dependent (see Fig. 1), with an offset of 0.44 ± 0.02 between the profiles seen at lower (E < 1.17 keV) and higher energy (E > 1.25 keV), the transition occurring quite abruptly at ~1.2 keV, consistent with the findings of Gotthelf & Halpern (2009). As shown in Fig. 2, the pulsed fraction (PF) decreases from ~15 per cent in the 0.4–0.6 keV energy range to <2 per cent in the 1.1–1.3 keV range, then grows again to ~15 per cent at E > 2 keV, in good agreement with the model by Gotthelf et al. (2010).

4 PHASE-RESOLVED SPECTROSCOPY

Thorough phase-integrated spectroscopy of RX J0822–4300 has been published by Hui & Becker (2006). We will focus here on phase-resolved spectroscopy. RX J0822–4300 lies in a very complex environment, which makes background subtraction a critical task. Using phase-integrated data, we evaluated an optimal selection of source events by maximizing the signal-to-noise ratio in the 0.3–10 keV range as
time-variable emission line in RX J0822−4300

Figure 1. Background-subtracted folded light curves for RX J0822−4300 in the soft energy range (0.46–1.17 keV, upper panel) and in the hard energy range (1.25–5.12 keV, middle panel). The lower panel shows the hardness ratio (hard to soft), normalized to its average value. Phase intervals used for phase-resolved spectroscopy are also marked.

Figure 2. Energy dependence of PF. The PF was evaluated in overlapping 0.2 keV energy bins, incremented in 0.1 keV steps, as the ratio between the number of counts above the minimum and the total number of counts. Background has been subtracted. A clear trend is apparent, with a minimum in the 1.1–1.3 keV energy range.

Figure 3. Residuals (in counts s$^{-1}$) of two-blackbody fits to the soft-phase spectra (see Fig. 1). A structure in the 0.6–0.9 keV range is seen in both epochs, although with different shape and intensity.

First, we repeated the exercise performed by Gotthelf & Halpern (2009), fitting a double-blackbody model to our data. A simultaneous fit to the four phase-resolved spectra was performed for each epoch. The blackbody normalizations were allowed to vary as a function of phase, while the temperatures and $N_{\text{H}}$ were held fixed in order to constrain a single value for all phase ranges. This model yields a reduced $\chi^2$ of 1.20 for 298 degrees of freedom (d.o.f.) and of 1.23 for 389 d.o.f for the first- and second-epoch data, respectively.

Although modulation of the emitting radii accounts for the bulk of the spectral variation, structured residuals in the 0.6–0.9 keV range are apparent in the soft phase both in the 2001 data set (as already reported by Gotthelf & Halpern 2009) and in our deeper 2009–10 data set, which confirms the existence of a phase-dependent spectral feature.

Very interestingly, while the phase-resolved best-fitting parameters do not change as a function of epoch – they can be linked in a simultaneous two-epoch fit (more details below) – the deviation from the continuum in the soft phase has a somewhat different shape in 2001 with respect to 2009–10 (see Fig. 3), suggesting a possible time-variability of the spectral feature.

Indeed, such variation is fully apparent when plotting together the two soft-phase spectra (see Fig. 4). To quantify the significance of the spectral change in a model-independent way, we compared the distributions of the source events’ energies observed in the two epochs using the Kolmogorov–Smirnov test. The probability of a statistical fluctuation producing the apparent difference in the energy range where the feature is seen ($\sim$0.6–0.9 keV) turned out to be $3 \times 10^{-6}$.

As a second step, in order to model the feature, we focused on the two soft-phase spectra. Following Gotthelf & Halpern (2009), we added a Gaussian emission line to the two-blackbody model. Indeed, this yields a much better fit with no structured residuals in the 0.6–0.9 keV range. As expected, the line component varies as a function of time, its central energy being higher in the first epoch ($\sim$0.80 keV) than in the second epoch ($\sim$0.73 keV). The significance of such line components was studied by calibrating the F-statistics using simulations of the null model (the double-blackbody model).
absorption line, as well as to two variable absorption lines ($\chi^2 = 1.23$ for 150 d.o.f. for the latter model).

Then, the whole analysis was repeated for the other phase intervals (hard, softening and hardening). No significant improvement in the fit was obtained by adding an emission line to the two-blackbody model (the same is true using absorption features). We assessed that, in each phase interval, the continuum did not change as a function of epoch and that there are no systematic variations between the first and second epochs in the 0.5–1 keV energy range (such results indicate that the long-term variability of the feature cannot have an instrumental origin).

As a final step, we performed a simultaneous fit to all the spectra based on the results described above. We used the two-blackbody plus emission-line model. The blackbody normalizations are phase-dependent, but not epoch-dependent; the line normalization is phase-dependent and its central energy is epoch-dependent. This yields a reduced $\chi^2 = 1.13$ for 691 d.o.f. in such models, $N_{\text{H}}$ is $(5.0 \pm 0.1) \times 10^{21}$ cm$^{-2}$, the warm blackbody has a temperature $kT_w = 265 \pm 15$ eV and a radius ranging from 2.27 km (soft phase) to 2.04 km (hard phase), and the hot blackbody has a temperature $kT_h = 455 \pm 20$ eV and a radius ranging from 0.53 km (soft phase) to 0.65 km (hard phase). The line component is narrow ($\sigma < 40$ eV).

In 2001, the line energy is $0.80 \pm 0.01$ keV and the equivalent width (EW) ranges from $\sim 53$ eV in the soft phase to $< 10–15$ eV in other intervals (where the line is not significant). In 2009–10, the line energy is $0.73^{+0.05}_{-0.05}$ keV and the EW ranges from $\sim 45$ eV (soft phase) to $< 12–18$ eV in other intervals. The unabsorbed flux of the line between 0.3 and 10 keV is $\sim 3$ per cent of the flux of the continuum in the same energy range.

5 DISCUSSION


To put such a peculiar result in context, we first note that our observations confirm the picture of RX J0822–4300 as a weakly magnetized neutron star. Indeed, we improved the upper limit on $P$, bringing the dipole component of the magnetic field down to $< 2.3 \times 10^{13}$ G at 3σ level. Based on larger statistics, we also confirm the geometric model by Gotthelf et al. (2010), explaining the phase-resolved thermal emission with two antipodal spots of different temperature (compare e.g. our Fig. 2 to their fig. 6). Lack of any measurable time-variation in the continuum properties suggests that the warm and hot regions are intrinsic, persistent features in the thermal map of the star. To explain such a large surface anisotropy for RX J0822–4300 (and for CCOs in general), we may consider that a large difference in intensity could exist between the internal and the external magnetic fields of the neutron star, as proposed by Turolla et al. (2011) to explain the properties of the low magnetic field soft gamma repeater SGR 0418+5729 (Rea et al. 2010). In our case, an internal (toroidal + poloidal) field of a few $10^{13}$ G would be large enough to effectively channel the heat flux from the core (Geppert, Küker & Page 2004, 2006), but would not induce crustal fractures with consequent magnetar-like bursting activity.

The most natural interpretation of the variable emission line is that of a cyclotron feature produced by electrons. If its central energy is associated with the fundamental $e^-$ cyclotron frequency, the magnetic field in the line-emitting region would be $(6–7) \times 10^{19}(1 + z) G$ (where $z \sim 0.25$ is the gravitational redshift). This is quite compatible with the upper limit from the spin-down rate.
The line is very narrow ($\sigma \leq 40$ eV). If it is a cyclotron line, then $\Delta E/E = A B / B$ and the relative variation of $B$ over the emitting region (conservatively) needs to be $\leq 10$ per cent. Thus, the line should be produced in a very compact region. A variation of the central energy of the feature would require a change either in the position of the emitting plasma within a non-variable magnetic field, or in the intensity of the magnetic field itself. Lack of changes in the phase-resolved continuum emission rules out simpler, purely geometric explanations such as precession of the neutron star.

To explain the generation of an emission line in the spectrum of an isolated neutron star, the possibility of cyclotron scattering of surface thermal photons by a geometrically-thin, optically-thin layer of plasma could be considered. However, under simple assumptions (emission from the entire star surface; plane-parallel geometry; pure, conservative scattering), a scattering layer would produce an absorption line. One might invoke a spatially limited scattering medium, possibly some distance away from the star surface. Photons coming from the part of the surface not covered by the layer could be scattered along the line of sight giving rise to an emission feature. The value of $B$ derived from the line energy is somehow smaller than the upper limit on the surface field, so the line could indeed form at some height in the magnetosphere. A confined medium seems also to be required by the results of phase-resolved spectroscopy which shows that the emission line is seen mostly when the cooler spot is into view. Still, such a picture seems rather contrived, since the nature of the layer and the mechanism keeping the plasma suspended and confined in a compact blob remains to be understood.

To ease the problem, an energy source unrelated to the surface thermal emission should be invoked to excite $e^{-}$ to higher Landau levels in the line-emitting region. Indeed, Nelson, Salpeter & Wasserman (1993) predicted that for neutron stars accreting at a low rate ($L_{\text{accr}} < 10^{32}$ erg s$^{-1}$), and endowed with magnetic fields of $10^{11} - 10^{13}$ G, accreting ions may lose energy to atmospheric electrons via magnetic Coulomb collisions. Electrons, excited to high Landau levels, radiatively decay and part of the cyclotron photons are expected to escape producing an emission line. According to Nelson et al. (1993), at $B < 10^{12}$ G, the fraction of the accretion-powered flux escaping in the line is expected to be very small ($\leq 5$ per cent), the largest part being reprocessed and emitted in a thermal continuum. Thus, one should postulate that the bulk of the X-ray luminosity of RX J0822$-4300$ is accretion powered, at variance with observations. It would require an accretion rate of $\sim 2 \times 10^{13}$ g s$^{-1}$ implying – under standard relations for propeller spindown (Menou et al. 1999) – a $P$ value more than 10 times larger than our upper limit. Although the model by Nelson et al. (1993) does not fit to our case, low-level accretion of supernova fallback material (which cannot be ruled out, based on X-ray timing, as well as on the optical upper limits set by Mignani et al. 2009) could play some role in generating an emission line in a low-$B$ atmosphere. A detailed investigation of such possibility is beyond the scope of this Letter.

We will not go into further speculations about the line-emitting mechanism. We stress that the evidence for time-evolution of the spectral feature is model-independent and represents to date the first evidence for variability in an ‘antimagnetar’ candidate. Likely, such ‘activity’ is related to a variation in the magnetic field of the star. An $\sim 10$ per cent decrease in $\sim 8$ yr seems vastly too steep to be attributed to the large-scale dipole field. Possibly, we are witnessing evolution of a localized multipole component, dominating close to the star surface. This would hint at the presence of a large internal field, as proposed to explain the anisotropic thermal map of the star. Precise X-ray timing, assessing the $P$ and measuring the star dipole field will add a crucial piece of information. Coupled with further sensitive phase-resolved spectroscopy to monitor spectral variability, this could help to solve the puzzles set by our results on RX J0822$-4300$ which would have important implications for the understanding of the nature of CCOs and of their relations with other families of neutron stars.

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