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Letter to the Editor

The hard X-ray emission of X Persei

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ABSTRACT

We present an analysis of the spectral properties of the peculiar X-ray pulsar X Per based on INTEGRAL observations. We show that the source exhibits an unusually hard spectrum and is confidently detected by ISGRI up to more than 100 keV. We find that two distinct components may be identified in the broadband 4–200 keV spectrum of the source. We interpret these components as the result of thermal and bulk Comptonization in the vicinity of the neutron star and describe them with several semi-phenomenological models. The previously reported absorption feature at ~30 keV is not required in the proposed scenario and therefore its physical interpretation must be taken with caution. We also investigated the timing properties of the source in the framework of existing torque theory, concluding that the observed phenomenology can be consistently explained if the magnetic field of the neutron star is $\sim 10^{14}$ G.

Key words. X-rays: binaries – pulsars: individual: X Persei – stars: neutron

1. Introduction

4U 0352+309 is a persistent, low-luminosity, long periodic accreting pulsar with a pulse period ~837 s and an X-ray luminosity $L_x \sim 10^{35}$ erg s^{-1} (White et al. 1976). The hard X-ray spectrum and the observed variations of the spin-period $|\dot{P}/P| \sim 10^{-4}$ yr^{-1} (Delgado-Martí et al. 2001) imply that the compact object is a neutron star.

The neutron star orbits the nearby *Be* star *X Persei* (d = 0.95 ± 0.2 kpc, Telting et al. 1998). The binary orbit is wide and almost circular, with an orbital period of about 250 d and eccentricity $e \sim 0.11$ (Delgado-Martí et al. 2001). The compact companion orbits relatively far away (~2 AU, Levine et al. 1999; Delgado-Martí et al. 2001) from the optical companion and does not pass through the disk of the *Be* star. Consequently, the source does not exhibit the outbursts at periastron typical for this class of sources. The observed X-ray luminosity is, however, three orders of magnitude higher (Delgado-Martí et al. 2001) than what is expected for accretion from a fast (~800 km s^{-1}) low-density stellar wind (Hammerschlag-Hensberge et al. 1980; Bernacca & Bianchi 1981). Indeed, to explain the observed X-ray luminosity, Delgado-Martí et al. (2001) suggested that accretion proceeds from a slower (~150 km s^{-1}) and denser wind extending from the circumstellar disk of the *Be* companion.

Another unusual aspect of 4U 0352+309 is its hard X-ray spectrum. Most accreting pulsars exhibit a power-law spectrum with a cutoff above $E \sim 20$ keV. X Per spectra in the hard energy range (≥10 keV) have been typically fitted with a thin thermal bremsstrahlung model with $kT \sim 10$ keV, sometimes with an additional hard-energy tail (White et al. 1976; Mushotzky et al. 1977; Frontera et al. 1979; Worrall et al. 1981). The "standard" cutoff power-law model has also been used (Frontera et al. 1979; White et al. 1983) although with an unusually low (~1 keV) cutoff energy.

The broadband X-ray spectrum of X Per is more puzzling. To describe the broadband (0.1–200 keV) BeppoSax spectrum, Di Salvo et al. (1998) used a model consisting of two power-law components. The first dominates at lower energies and is modified by an exponential cutoff at ~2 keV. The second is harder and is characterized by a low-energy turnover and a cutoff at ~65 keV. Di Salvo et al. (1998) argued that the partially thermalized emission from the atmosphere of the neutron star is responsible for the soft part of the spectrum. The hard part was interpreted either as cyclotron emission (Nelson et al. 1995) in a strong magnetic field, or was caused by high-temperature (~90 keV) thermal bremmstrahlung on electrons accelerated in a collisionless shock above the surface of the neutron star. Coburn et al. (2001) described the broadband (4–120 keV) RXTE spectrum of the source as a combination of a blackbody at low energies ($kT \sim 1.8$ keV) and a power law modified by a broad absorption feature at ~30 keV, which the authors interpreted as a cyclotron resonance scattering feature (CRSF). The magnetic field was therefore estimated to be $B \sim 2.6 \times 10^{12}$ G.

The spin period of 4U 0352+309 is peculiarly long. As expected for wind accretion, it varies erratically, although both spin-up and spin-down trends with $|\dot{P}/P| \sim 10^{-4}$ yr^{-1} have been identified (Delgado-Martí et al. 2001). The pulse-profile is single-peaked and sinusoidal. It changes very little with energy, although there is some hardening at peak minimum and maximum (Di Salvo et al. 1998; Coburn et al. 2001).

In this paper we focus on the spectral properties of the source as observed by INTEGRAL. We show how the broadband continuum spectrum of X Per is unusually hard and has two distinct humps, which we interpret as the result of thermal and bulk Comptonization in the accretion flow close to the surface of the neutron star. Similarities with other sources are also discussed.

2. Data and analysis

The INTErnational Gamma-Ray Astronomy Laboratory (INTEGRAL), launched in October 2002 by the European Space Agency (ESA) is equipped with theree co-aligned coded mask instruments: ISGRI (Integral Soft Gamma Ray Imager, Ubertini et al. 2003), JEM-X (Joint European

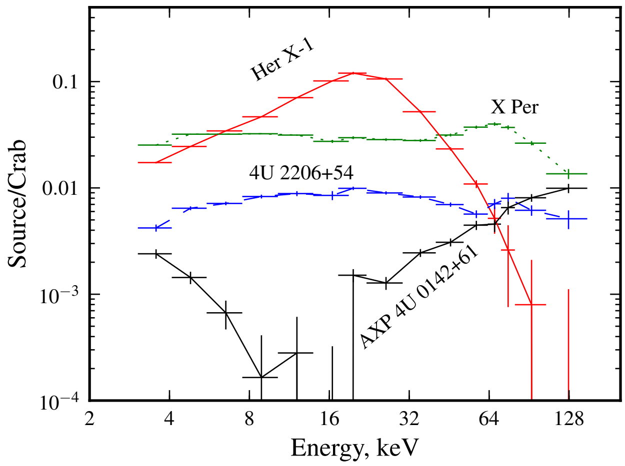

Fig. 1. Crab-normalized broadband spectra for Her X-1 (a typical accreting pulsar), X Per, 4U 2206+54 (a source that we argue is similar to X Per), AXP 4U 0142+61 (brightest of the anomalous X-Ray pulsars). Note how hard the spectrum of X Per is compared to Her X-1.

X-ray Monitor, Lund et al. 2003) and SPI (Spectrometer on INTEGRAL, Vedrenne et al. 2003).

To measure the broadband spectrum of the source we used the available archival data with X Per within the full-coded field of view of the JEM-X instrument (which has the smallest field of view among three instruments). This results in a total effective exposure of about 400 ks in 295 pointings from MJD 53 948 to 54 874. The data were reduced with the standard software OSA-9.0 and the set of calibration files IC-9.0 provided by ISDC[1]. For SPI imaging we used the *spiros* branch of the analysis pipeline.

The ISGRI image immidiately revealed something peculiar: unlike most other accreting pulsars, X Per was confidently detected (at 8.5σ) in the 100–200 keV energy range. Indeed, in this energy range X Per is the only source detected with significance greater than 5σ in the ISGRI field of view. This is not because the source is close to us. If other nearby *Be* X-ray binaries (with $d \sim 2{-}3$ kpc like Her X-1 or Vela X−1) were as hard as 4U 0352+309, they would be just a factor of 10 weaker and therefore easily detectable with the available ISGRI exposures.

The comparison of the broadband spectrum of X Per with that of other pulsars (see Fig. 1) shows that X Per is relatively bright at low energies, is fainter than a typical pulsar in the 8–40 keV range, but outshines its peers above ∼50 keV[2]. To perform a detailed spectral analysis we extracted the pulse-phase-averaged spectrum of X Per using data from the ISGRI, SPI, and JEM-X1 instruments (JEM-X2 was switched off during most of the observations, therefore there were few usable data).

To describe the spectrum we first used slightly modified versions of the models used by Di Salvo et al. (1998)[3] and by Coburn et al. (2001)[4]. Both models aim to mimic characteristic features of a Comptonization spectrum, therefore we also attempted to use a true Comptonization model derived from first principles (Titarchuk 1994) with two components of independent temperatures and optical depths. In all cases photoelectric absorption was included with the column depth fixed to 2×10^{21} atoms cm^{-2} (Haberl 1994; Di Salvo et al. 1998) since INTEGRAL does not have the low-energy coverage required to constrain it. The results are summarized in Table 1 and Fig. 2.

The best-fit values of the corresponding models are consistent with those reported previously by Coburn et al. (2001) and Di Salvo et al. (1998). Independently of the model used, two distinct "humps" are identified in the Ef_E spectrum (see Fig. 2). At lower energies the spectrum is similar to that typically observed in other HMXBs. It can be described as a cutoff power law, although the cutoff energy is quite low. At higher energies, however, a second "hump" starts to dominate and makes the spectrum unusually hard with a cutoff energy around 60 keV.

3. Discussion

The broad band spectrum and the CRSF. First we briefly discuss the interpretation of the broadband spectrum and the nature of the absorption feature proposed by Coburn et al. (2001). As already stated, the double "hump" Ef_E spectrum of the source can be described by the models by Coburn et al. (2001) and Di Salvo et al. (1998). We observe, however, that the additional broad absorption-like feature suggested by Coburn et al. (2001) is only required when a blackbody component is combined with a relatively steep power law with a very hard cutoff. But this absorption line is not necessary when the low-energy part of the spectrum is modeled with a power law rolling off at relative soft energies (Di Salvo et al. 1998) or, in our preferred interpretation, with a Comptonization model. The presence of the absorption feature is therefore model-dependent and its interpretation as a CRSF should be taken with caution. This makes the estimate of the B field in the range of 10^{12} G questionable.

Di Salvo et al. (1998), following early predictions of Nelson et al. (1995), suggested that the hard part of the spectrum is caused by cyclotron *emission* in the vicinity of the polar caps. In this scenario the plasma is stopped on the neutron star polar caps via Couloumb collisions at low accretion rates. A fraction (up to 5%) of the kinetic energy of the protons is transferred to the electron motions *transverse* to proton velocity (and magnetic field), thus leading to Landau level excitations. This implies the formation of a broad ($E/\Delta E \sim 2{-}4$) cyclotron *emission line*, which can be observed if photons are not thermalized in the atmosphere of the neutron star. Coburn et al. (2001) criticized this interpretation, arguing that the observed spectrum is not consistent with the relatively narrow line predicted by Nelson et al. (1995). In addition, we observe that the cyclotron emission scenario is ruled out by energetic considerations. From the observed broadband spectrum of X Per we find that the soft and hard components contribute ∼60% and 30% of the total luminosity, respectively[5], with the hard component being a factor of 10 stronger than that predicted by Nelson et al. (1995).

To understand the nature of its hard component, it is interesting to compare X Per with other accreting pulsars. At high accretion rates (above $\sim 10^{16}$ g s^{-1}) the accretion flow in the vicinity of the neutron star is stopped by the radiation pressure of the X-ray emission from the pulsar in a so-called radiation-dominated shock with an accretion column forming below this shock (Basko & Sunyaev 1976). The X-rays emerging from the polar caps are thermalized in the accretion column, producing the typical cutoff power-law component observed in the spectra of accreting pulsars (Becker & Wolff 2007). At low accretion rates, as for X Per, the accretion column does not form (Basko & Sunyaev 1976). However, the flow is optically thick along the accretion direction. An accretion rate of $\sim 10^{15}$ g s^{-1}

[1] http://www.isdc.unige.ch/integral/analysis

[2] For this comparison we used the quick-look data provided by ISDC HEAVENS (Walter et al. 2010).

[3] No rollover for the hard component is required.

[4] Cutoff for the hard component is required.

[5] The hard component contributes only about 10% of photons.

Table 1. Best-fit results for the X-Per broadband spectrum obtained with INTEGRAL and fitted with the discussed models.

Model	Low energy part					High energy part			
Di Salvo et al. (1998)	$E^{\dagger}_{\rm cut,low}$	$E^{\dagger}_{\rm fold,low}$	$\Gamma_{\rm low}$		$A_{\rm low}$	$E^{\dagger}_{\rm cut,high}$	$E^{\dagger}_{\rm fold,high}$	$\Gamma_{\rm high}$	$A_{\rm high}$, 10^{-3}
	$4.7^{+1.3}_{-0.9}$	$9.1^{+3.0}_{-2.7}$	$1.4^{+0.2}_{-0.3}$		$0.11^{+0.05}_{-0.04}$	$55.0^{+8.3}_{-4.4}$	$32.9^{+6.3}_{-5.6}$	$0.7^{+0.5}_{-0.6}$	2^{+6}_{-1}
Coburn et al. (2001)	$kT^{\dagger}_{\rm bb}$	$E^{\dagger}_{\rm cyc}$	$\sigma^{\dagger}_{\rm cyc}$	$\tau_{\rm cyc}$	$A_{\rm bb}$	$E^{\dagger}_{\rm cut}$	$E^{\dagger}_{\rm fold}$	Γ	$A_{\rm pl}$
	$1.69^{+0.08}_{-0.07}$	$33.2^{+1.2}_{-1.2}$	$7.7^{+9.9}_{-1.5}$	$5.5^{+2.1}_{-1.5}$	$0.0027^{+0.0004}_{-0.0004}$	$67.5^{+5.1}_{-5.8}$	$48.7^{+11.6}_{-9.5}$	$1.92^{+0.04}_{-0.04}$	$0.16^{+0.03}_{-0.02}$
CompTT + CompTT	$kT^{\dagger}_{\rm e,low}$	$\tau_{\rm low}$	$T^{\dagger}_{0}$		$A_{\rm low}$	$kT^{\dagger}_{\rm e,high}$	$\tau_{\rm high}$	$T^{\dagger}_{0}$	$A_{\rm high}$, 10^{-3}
	$4.6^{+0.5}_{-0.8}$	$9.2^{+1.3}_{-0.7}$	$0.83^{+0.04}_{-0.06}$		$0.036^{+0.008}_{-0.005}$	$15.3^{+1.5}_{-0.5}$	$\gtrsim 6$	$0.83^{+0.04}_{-0.06}$	$0.5^{+0.7}_{-0.1}$

Notes. Here $kT_{\rm bb,e,0}$ are the blackbody, electron or seed temperatures for the blackbody and Comptonization models, Γ is the power-law photon index, $E_{\rm cut,fold}$ are the cutoff and fold energies for the cutoff power-law component. The "low" and "high" indices refer to the two spectral components. † [keV].

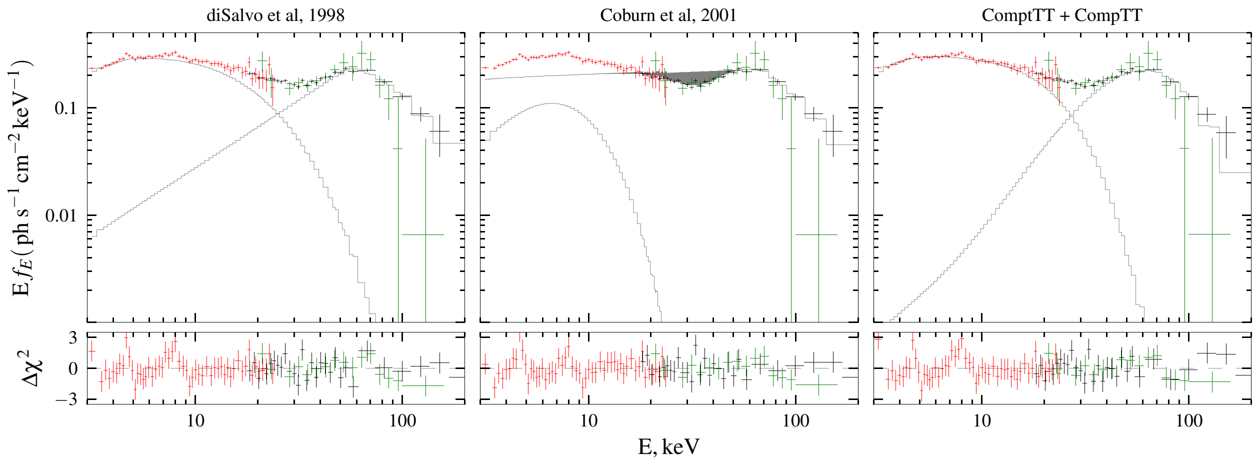

Fig. 2. Ef_E spectrum of X Per observed by INTEGRAL. The best-fit spectra of the three different models discussed in the text and their residuals are shown. Data from ISGRI (black), JEM-X (red) and SPI (green) instruments were used. The contribution of the single model components is also shown. For the model by Coburn et al. (2001) (middle panel), we also show (shadowed area) the effect of including an absorption-like line, which is required by the specific continuum.

corresponds to $\sim 10^{29}$ particles cm^{-2} s^{-1} for an accretion flow with radius $R \sim 500$ m. On a time scale of 10^{-5} s (or $\sim$2 km assuming a free-fall velocity of $\sim 0.6c$) a column density of $\sim 10^{24}$ particles cm^{-2}, equivalent to $\tau \sim 1$ for Compton scattering, can be reached. Soft photons emerging from the polar caps will most likely scatter off relativistic electrons along the accretion flow and, therefore, one expects "bulk" Comptonization to play an important role in the spectral formation (Becker & Wolff 2005). Note that at low accretion rates photons can relatively easily escape perpendicularly to the accretion flow along the side walls without being thermalized. Becker & Wolff (2005, 2007) were able to qualitatively describe the observed spectrum of several sources including X Per with purely bulk Comptonization, albeit in a limited energy range. Note that a cutoff power law spectrum is still expected to emerge from the vicinity of the polar cap, since thermal Comptonization is still expected to play a role. This scenario can be described by the two spectral components we used to fit the INTEGRAL data. This is of course a qualitative explanation and detailed spectral calculations are needed. In particular, cyclotron emission should not be ignored, even if it is not the dominant component. The pulse phase dependence of the spectrum could certainly help in clarifying the suggested scenario. Unfortunately, the statistics of the INTEGRAL data did not allow us to constrain the phase-dependent parameters.

Link with other sources and the magnetic field. Dynamical or "bulk" Comptonization (Blandford & Payne 1981; Psaltis & Lamb 1996) has been invoked to describe spectra of various sources, most notably the hard tails in the spectra of low-mass X-ray binaries (Farinelli et al. 2008) and accreting X-ray pulsars (Becker & Wolff 2007). Torrejón et al. (2004) combined thermal and bulk Comptonization to describe the broadband spectrum of 4U 2206+54 and predicted, based on their best-fit parameter, the wind-accretion nature of the source. This prediction was later confirmed with the discovery of pulsations with period $\sim$5560 s (Reig et al. 2009; Finger et al. 2010). Finger et al. (2010) determined that despite its long period and accretion rate, the source spins down. This is possible only if the magnetic field is $B \geq 10^{15}$ G, i.e., lies in magnetar range. X Per and 4U 2206+54 are strikingly similar because they both accrete from wind, have a long spin period and continue to spin-down on average. They have a similar spectrum and luminosity, and as we have shown, there is likely no cyclotron line in X Per. These consideration raise a key question: what is the magnetic field of X Per? We can use the torque theory to get some insight on the anwer to this question. As we extensively discussed in Doroshenko et al. (2010), following Illarionov & Kompaneets (1990), the dipole component of the magnetic field of wind accreting X-ray pulsars can be estimated as

$$B \approx 4 \times 10^{11}\,\mathrm{G} \left(\frac{k_{\mathrm{w}}}{0.25}\right)^{7/8} \left(\frac{k}{2/3}\right)^{-7/8} \left(\frac{\xi}{0.87}\right)^{-7/8} \left(\frac{\dot{M}_{\mathrm{eq}}}{10^{15}\,\mathrm{g/s}}\right)^{1/2} \quad (1)$$
$$\times \left(\frac{\upsilon}{800\,\mathrm{km\,s^{-1}}}\right)^{-7/2} \left(\frac{P}{837\,\mathrm{s}}\right)^{7/8} \left(\frac{P_{\mathrm{orb}}}{250\,\mathrm{d}}\right)^{-7/8} \left(\frac{M}{1.4\,M_{\odot}}\right)^{2} \left(\frac{R}{10^{6}\,\mathrm{cm}}\right)^{-3},$$

here $k_{\mathrm{w}}, k, \xi \simeq 1$ are dimensionless coefficients, υ is the velocity of stellar wind, P, P_{orb} are spin and orbital periods of neutron star, and M, R are mass and radius of the neutron star. For X Per, fast accretion winds with a terminal velocity of $800\,\mathrm{km\,s^{-1}}$ (Hammerschlag-Hensberge et al. 1980) would imply a magnetic field of $B \sim 10^{12}\,\mathrm{G}$. On the other hand, Delgado-Martí et al. (2001) argued that to explain the observed luminosity and pulse period change rates of X Per, a slow wind subcomponent extending from the outskirts of the *Be*, with velocity $\upsilon \sim 150\,\mathrm{km\,s^{-1}}$ must be invoked. A slow wind implies more captured orbital angular momentum and therefore, from Eq. (1), a magnetic field in the "magnetar" range, i.e., $B \sim 10^{14}\,\mathrm{G}$. As discussed in Doroshenko et al. (2010), other torque models found in literature for wind accretion (Davidson & Ostriker 1973; Davies et al. 1979; Bisnovatyi-Kogan 1991) give similar values.

Trümper et al. (2010), trying to link the quiescent emission of magnetars to that of accreting pulsars, have suggested bulk Comptonization as the key mechanism for the formation of the quiescent spectra of anomalous X-ray pulsars and discussed the hard spectrum of 4U 2206+54 as the link between the two classes of sources. Given the similarities with 4U 2206+54, the same considerations can be extended to X Per. That the torque theory for both accreting pulsars suggests a magnetic field in the magnetar range makes this idea worthy of more detailed investigation.

We note, however, that despite all similarities between the spectra of 4U 2206+54, X Per and AXPs (particularly 4U 0142+61), significant differences in the spectra (see Fig. 1), not discussed by Trümper et al. (2010), are evident. The spectrum of AXP 4U 0142+61 extends to higher energies with no detectable cutoff, while the soft component is much less prominent. A detailed explanation of these differences is beyond the scope of this paper. However, we believe that in the scenario outlined by Trümper et al. (2010), the differences can be qualitatively explained by the lower luminosity of AXP 4U 0142+61. Indeed, we interpret the low-energy component as Comptonized emission from the vicinity of the neutron star. Comptonization is more effective at higher densities, meaning this component is likely more prominent for X Per, because it is accreting at a significantly higher rate. On the other hand, the cutoff energy of the high-energy component in the bulk Comptonization scenario depends on the ratio between the average thermal and bulk energies (Farinelli et al. 2008). The bulk energy of the flow is the same in both cases, while the lower luminosity of 4U 2206+54 implies that less X-ray photons heat the plasma. Bulk Comptonization is more important in this case and the cutoff shifts to higher energies. Detailed calculations including the cyclotron cooling of the plasma are required to confirm our qualitative scenario.

4. Conclusions

We analyzed INTEGRAL observations of the low-luminosity accreting pulsar X Per. Our main conclusions are:

- The source is significantly detected with ISGRI above 100 keV and shows the hardest spectrum among accreting pulsars.
- We successfully modeled, in line with previous findings, the 4–200 keV broadband spectrum of the source with a two-component spectrum. No CRSF is necessary to model our data. We interpret the lower energy component as the result of thermal Comptonization. This component is, compared to other accreting pulsars, significantly reduced most likely because there is no accretion column.
- The harder spectral component is interpreted for the first time as the result of the dynamical Comptonization in the accretion flow of photons emerging from the polar cap.
- We showed that according to the current torque theory and taking into account the expected terminal wind velocity, a magnetic field of $\sim 10^{14}$ G has to be expected for X Per.
- We discussed similarities of X Per with the slow accreting pulsar 4U 2206+54 and, as suggested, by Trümper et al. (2010) with AXP 4U 0142+61.

The low-luminosity, yet bright pulsars such as X Per and 4U 2206+54 can be good laboratories to verify bulk Comptonization models because thermal Comptonization is expected to be much less important than in high-luminosity sources. Although we cannot conclude on the intenisty of the magnetic field of the neutron star in X Per, we believe the "high field" scenario presented above is coherent and worth further investigation. In this sense, X Per and 4U 2206+54 are also ideal candidates for all efforts aiming at linking AXPs to lower B-field accreting pulsars.

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