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INTEGRAL view on X Per

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Summary

After more than 40 years of studies, surprisingly little is known about properties of accreting pulsars at low-luminosities, yet these may constitute the majority of neutron star binaries in galaxy (Liu & Li 2006). The *eRosita* survey will reveal many such objects, but to identify them it is crucial to understand the properties of known sources beforehand. Here we present the results of an analysis of *INTEGRAL* observations of the nearby low-luminosity accreting pulsar X Per. We discuss the nature of it is very hard spectrum and implications for the *eRosita* survey.

X Persei

4U 0352+309 or X Per is a persistent accreting pulsar with a low X-ray luminosity of $L_x \sim 10^{35}\,\mathrm{erg\,s^{-1}}$ and a long pulse period of about 837 s (White et al. 1976). The neutron star orbit is the nearby *Be* star *X Persei* ($d = 0.95 \pm 0.2$ kpc, Telting et al. 1998). The binary orbit is wide and almost circular with $P_{\mathrm{orb}} \sim 250$ d and $e \sim 0.11$ (Delgado-Martí et al. 2001). This implies that the neutron star is always 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* companion, meaning the source exhibit is no outbursts around the periastron. Still X Per is a factor of 1000 (Delgado-Martí et al. 2001) brighter than one could expect assuming that accretion proceeds directly from the thin, fast ($v \sim 800\,\mathrm{km\,s^{-1}}$) wind revealed by optical observations (Hammerschlag-Hensberge et al. 1980; Bernacca & Bianchi 1981). Delgado-Martí et al. (2001) suggested that a slower wind component extending from the *Be* disk probably fuels the accretion.

The X-ray spectrum is known to be pretty hard. 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 Coburn et al. (2001) interpreted as a cyclotron resonance scattering feature (*CRSF*). This implies a magnetic field of $B \sim 2.6 \times 10^{12}$ G.

Observations

We analyzed available *INTEGRAL* archival data (about 400 ks exposure) with X Per in the FOV of all instruments. X Per is confidently detected in the 100-200 keV energy range in the combined IBIS/ISGRI mosaic image (at 8.5σ, see Fig. 1). Note that if other nearby *Be* X-ray binaries (with $d \sim 2-3$ kpc such as GX 301−1 or Vela X−1) were as hard as X Per, they'd be just a factor of 10 fainter and thus easily detectable with available ISGRI exposures, however they are not. Why X Per is so hard?

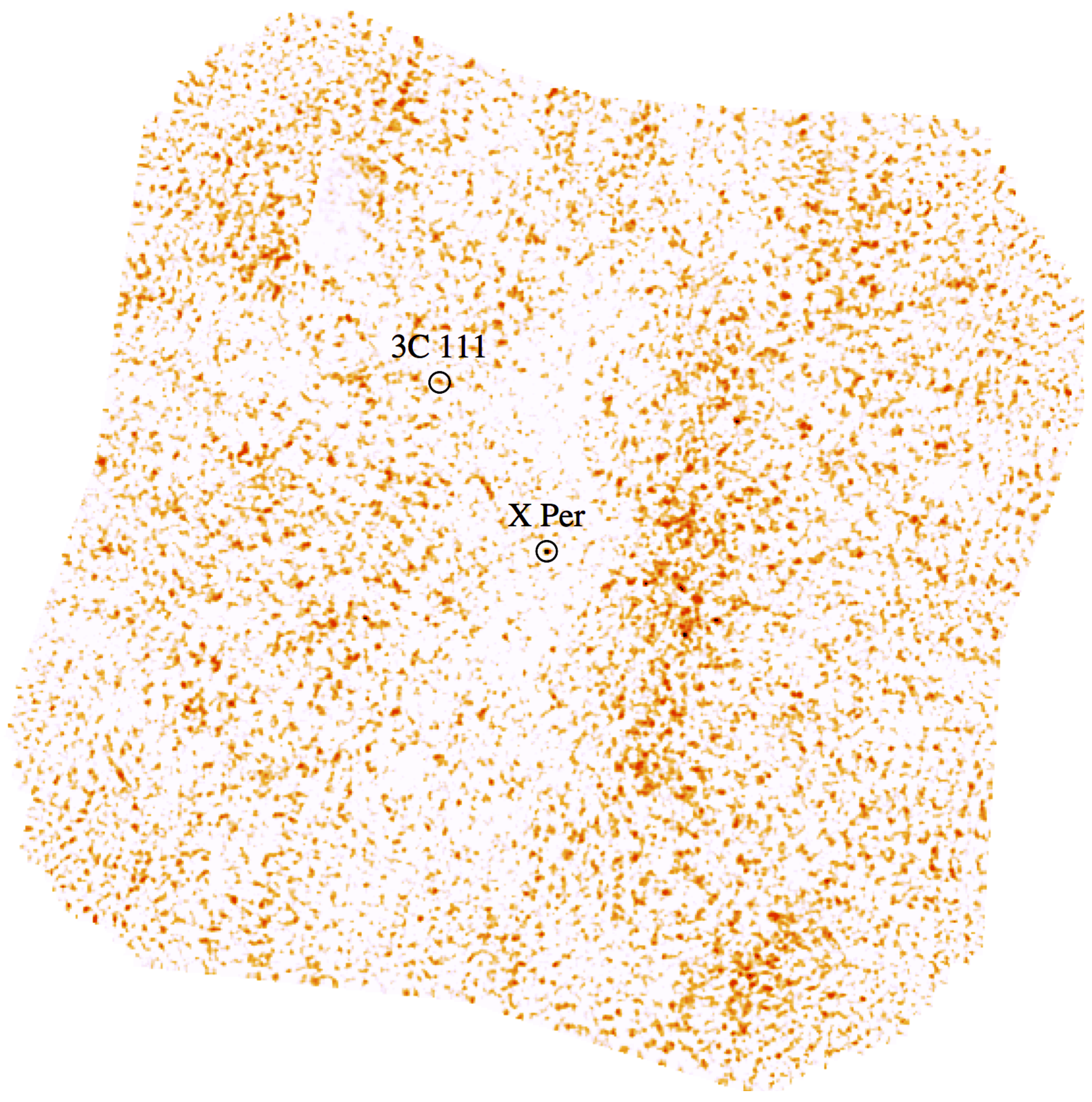

Figure 1: IBIS/ISGRI significance map of region around X Per in energy range 100−200 keV (all data used). X Per is the only significant source in this energy range in FOV.

The broadband spectrum

To model the spectrum we try several models, including slightly modified versions of models previously used by di Salvo et al. (1998) (our data did not require low-energy rollover for the high energy component) and Coburn et al. (2001) (power law had to be modified by high energy cutoff). Additionally we adopted a model which consisted of two comptonization components (Titarchuk 1994). In all cases photoelectric absorption was included with column depth fixed to 2×10^{21} atoms $\mathrm{cm^{-2}}$ (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 Fig. 2.

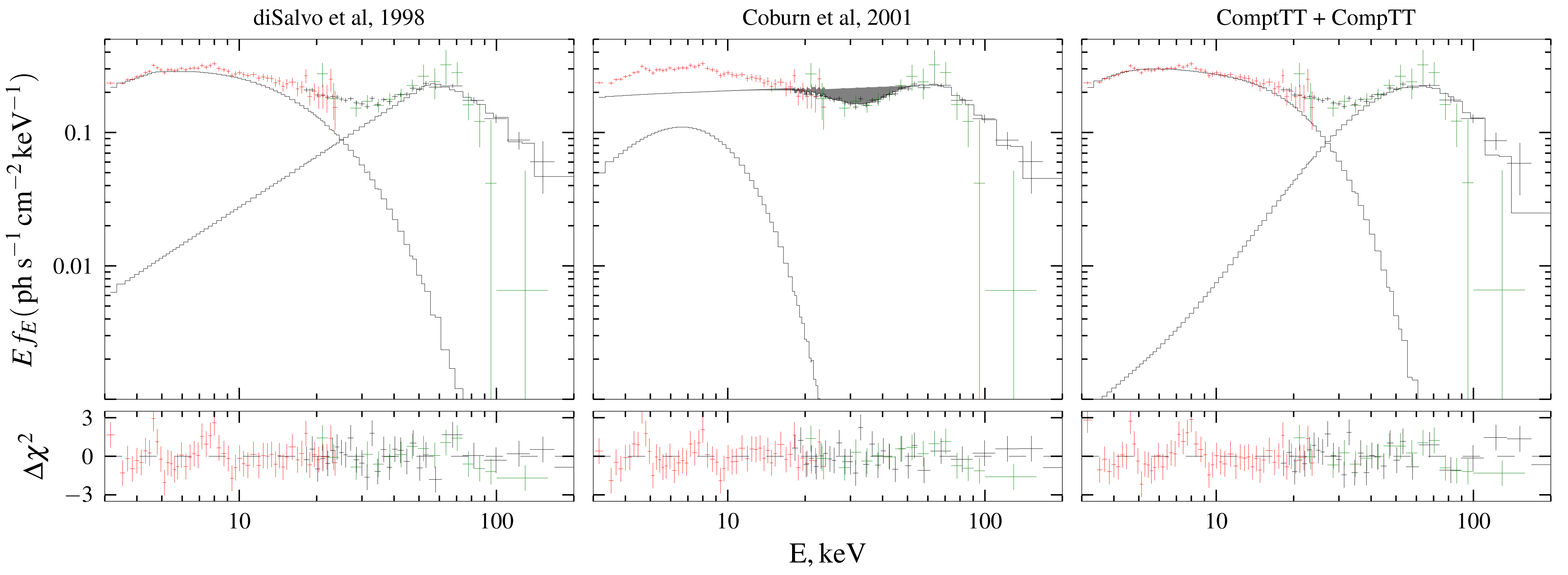

Figure 2: Unfolded spectrum of X Per and residuals as observed by INTEGRAL when fitted with different models. Data from IBIS (black), JEM-X (red) and SPI (green) instruments was used. Two spectral components with temperatures of ~ 5 and 15 keV are identified at low and high energies. Their contribution, almost equal from an energetic point of view, is also shown. For the case where model proposed by Coburn et al. (2001) is used (middle pane), the impact of inclusion of the absorption feature (required by the fit) is also shown (shaded area). Note the discontinuity in the continuum around the same energy.

di Salvo et al. (1998) argued that the hard part of the spectrum is due to cyclotron *emission* in the vicinity of the polar caps (Nelson et al. 1995). A line-like hard component is predicted which is, however, not consistent with the observed spectrum (Coburn et al. 2001). Moreover, Nelson et al. (1995) estimates the hard component contribution to the total flux is only about 5%. This is not consistent with our *INTEGRAL* spectrum: we estimate that the hard component contributes $\sim 40\%$ to the total flux.

We have also performed pulse-phase resolved spectral analysis. Spectral parameters in pulse maximum and minimum are similar. The main difference is that the contribution of the hard component increases significantly in pulse minimum (see Fig. 3).

We argue that "bulk" comptonization in accretion flow might be responsible for the hard component. This scenario was discussed by Trümper et al. (2010) for persistent emission of AXPs. The observed cutoff energy/temperature of the hard component $\sim 55/15$ keV ⇔ $0.25c$ are consistent with free-fall velocity $v_{ff} = \sqrt{\frac{2GM}{R}} \simeq 0.25c$ @50 km. This scenario is also consistent with our phase-resolved analysis: up-scattering in the accretion flow shall reduce the fraction of pulsed X-rays, so one can anticipate an increased contribution of the hard component in the pulse minimum.

Regardless of the nature of the two component spectrum, the absorption feature at 30 keV appears most likely due to imperfect modeling of the continuum, and is probably not a CRSF.

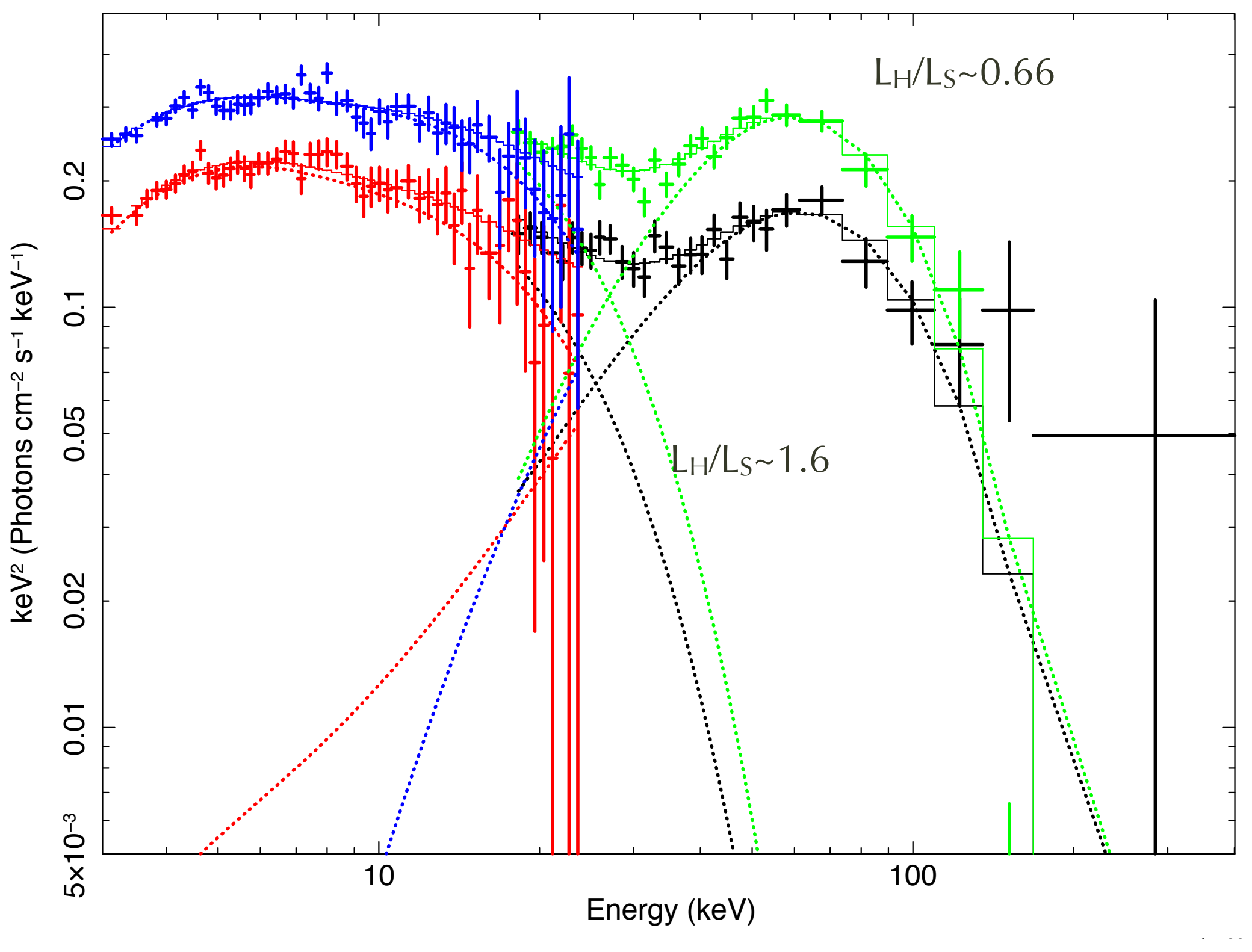

Figure 3: Comparison of the broadband spectrum in maximum (above) and minimum of sine-like pulse profile of X Per. Note how the spectrum hardens during the minimum.

In *eRosita* context

Average exposure of 2 ks in the Galactic plane implies a limiting flux of $\sim 10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ in the 2-10 keV energy range (M. Bursa et al) for the *eRosita* survey phase. Sensitivity for softer band is better, but HMXBs are clustered in the Galactic plane and thus are strongly absorbed. For comparison the *INTEGRAL* all-sky survey reaches about $10^{-11}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ in 20-40 keV energy range (Krivonos et al. 2007), so *eRosita* will be useful also for Galactic science. The luminosity function of Galactic HMXBs may be approximated as (Grimm et al. 2002):

$$N(>L) \simeq 20 \times \left(\frac{L_x}{10^{36}\,\mathrm{erg\,s^{-1}}}\right)^{-0.65}.$$

Note that it is poorly constrained from the observational point of view below $L_x \sim 10^{35}\mathrm{erg\,s^{-1}}$. The *eRosita* survey will be able to detect all Galactic sources with $L_x \geq 10^{34}\,\mathrm{erg\,s^{-1}}$, so we can estimate that there should be at least ~ 300 pulsars for $L_x \in 10^{34} - 10^{35}\,\mathrm{erg\,s^{-1}}$, which are difficult to detect in existing surveys, which will be detected by *eRosita*. Our results on X Per suggest that these might be identified among others by their very hard spectrum, particularly using ART-XC data.

Conclusions

- for an accreting pulsar, X Per has extremely hard spectrum and is detected by ISGRI up to 200 keV
- the two component spectrum can be interpreted as the result of thermal and bulk comptonization in the vicinity of neutron star
- an absorption feature at ~ 30 keV is only required for particular spectral model, so it's most likely not a CRSF
- many X Per-like sources are expected to be found in the *eRosita* survey which may be identified by their hard spectra.

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