Modelling X-ray beacons in curved space time

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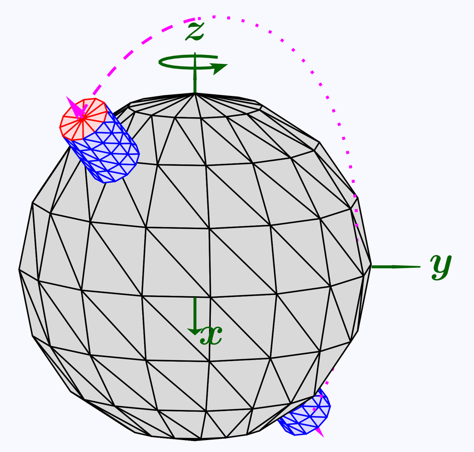
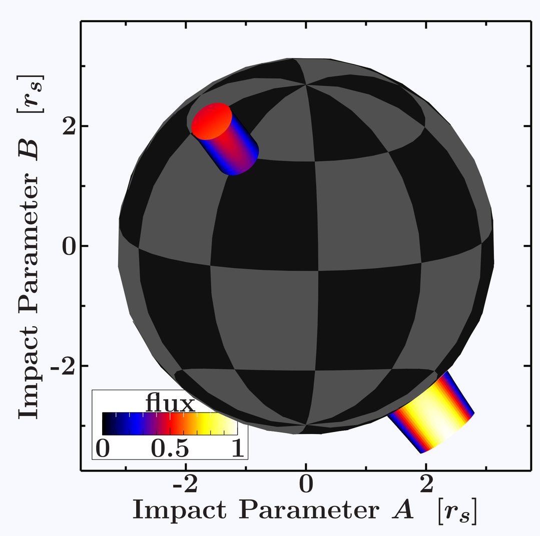
Abstract

In accreting X-ray pulsars, strong magnetic fields funnel matter onto the magnetic poles of neutron stars forming localized emission regions for beamed X-rays. As the pulsars rotate, very characteristic periodic patterns, so called pulse profiles, are observed, which show a broad range of complexity. Because of the extreme compactness of neutron stars, investigating the information contained in these profiles requires to account for general relativistic effects, like light bending, which can lead to complex and non-intuitive connections between the observed pulse profiles and the intrinsic geometry.
We have developed a fast and flexible light bending code, which calculates the observed time and energy dependent flux for arbitrary geometries and emission patterns of the emission regions. We present a detailed study and interpretation of the formation of theoretical pulse profiles and their comparison to observations.

Light Bending



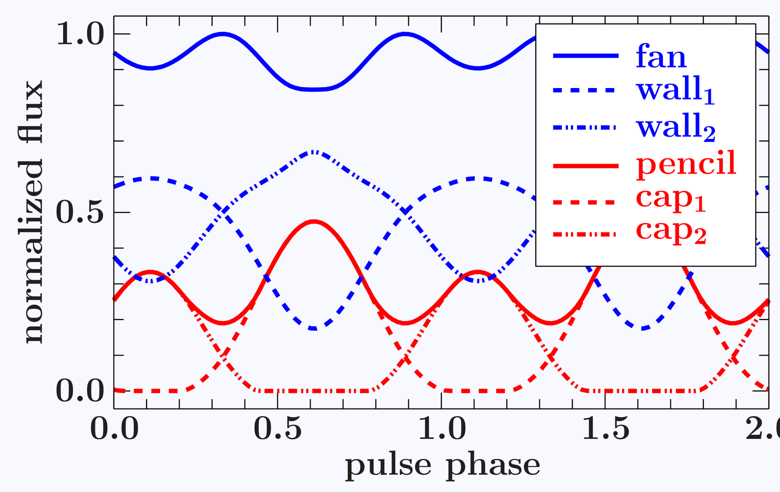
Geometrical structure of a neutron star with two symmetric, antipodal and cylindrical accretion columns.



Relativistic projection of the NS in the left figure onto the observer plane in units of Schwarzschild radii, r_s.

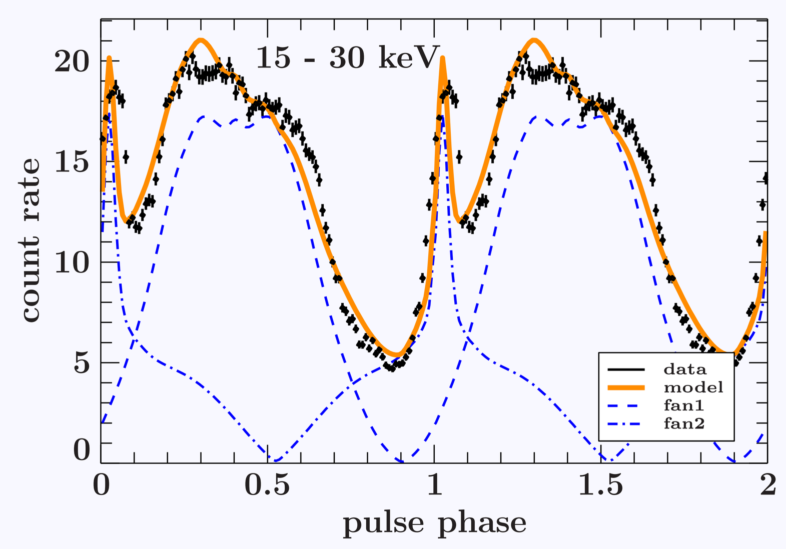
We have developed a self-consistent general relativistic ray-tracing code to obtain the spatially resolved, time and energy dependent observed flux of an accreting neutron star (NS). All relevant relativistic effects are accounted for within the Schwarzschild metric. The code follows a forward approach allowing physical input parameters, e.g., mass and radius of the NS, size and location of the accretion column(s). An arbitrary shaped geometrical structure of the emission region is combined with a freely chosen emission pattern. The trajectory of the emitted photons are then calculated to obtain the flux in the rest frame of a distant observer.

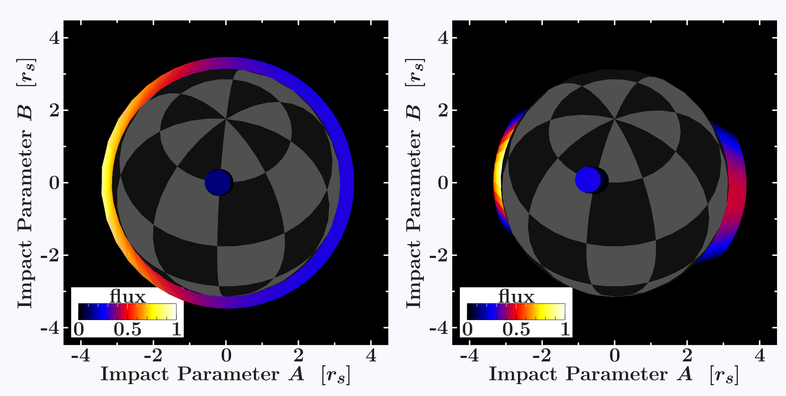
Light Bending: geometry + beam pattern(s) → energy- & time-resolved observed flux



Pulse profiles for different emission regions of the neutron star setup shown on the left. Note that the peaks in the pulse profile of the **fan** emission do not correspond to the peaks of its individual components as one may assume at first.

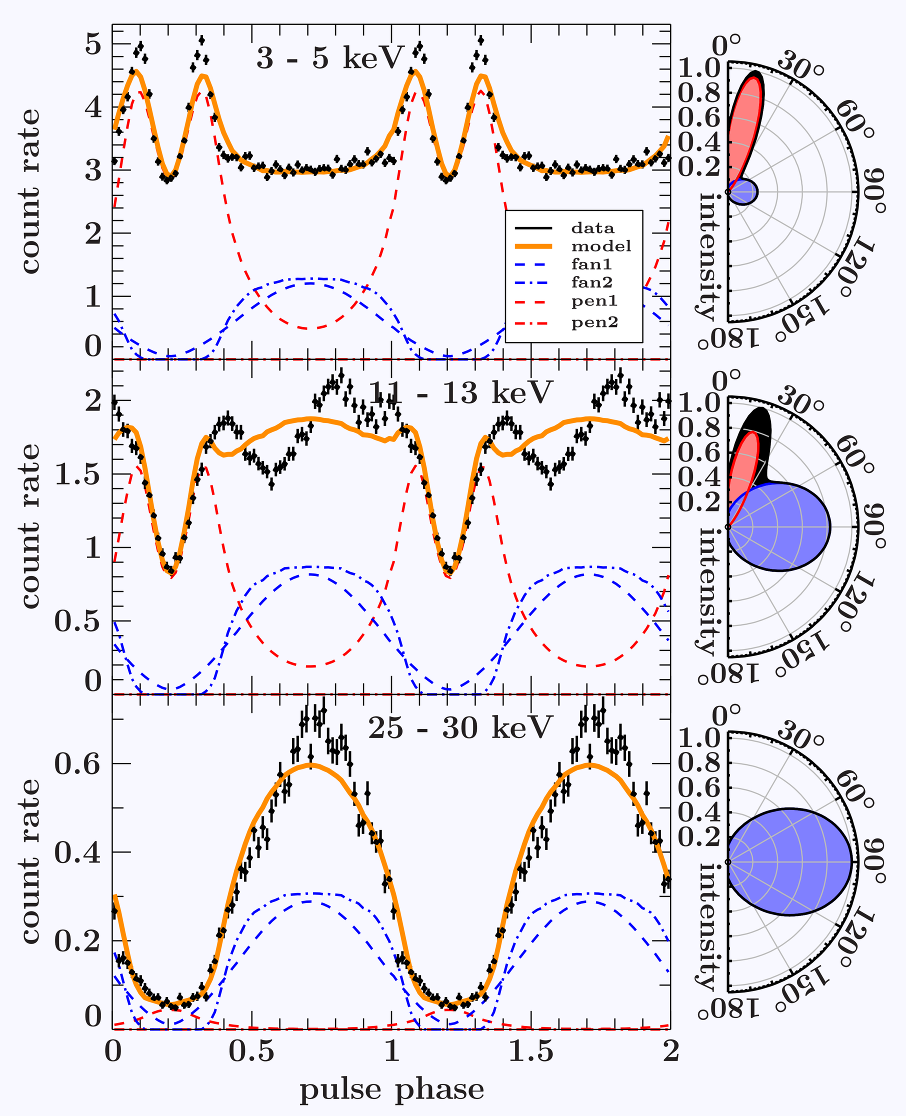
KS 1947+300





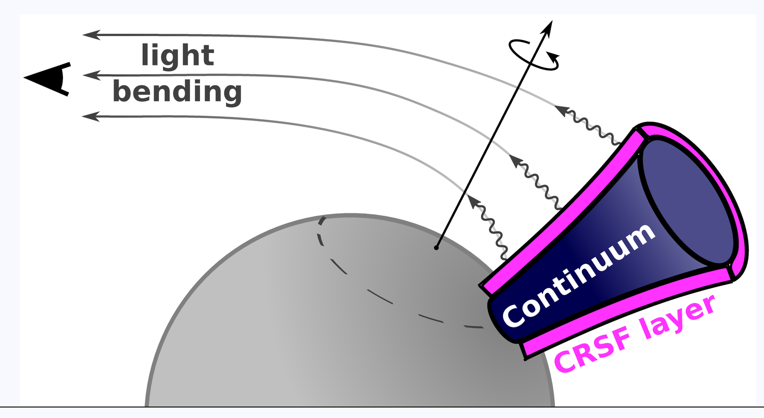
The **pulse profile** of KS 1947+300 at energies above 15 keV (*NuSTAR*) shows a peculiar, narrow peak which does not occur at low energies (Ballhausen et al., 2016). It is very unlikely that the dip is related to some sort of absorption (e.g., accretion stream) at this high energies.
Such a **peak** can be produced by a **strong light bending** effect when the line of sight is (almost) aligned with the magnetic field axis, i.e., when one of the accretion columns is on the opposite side of the neutron star. If this accretion column is sufficiently high ($\gtrsim 1$ km) it will become visible as a kind of **Einstein ring** around the neutron star (see projections below). This effect causes a significant increase of the observed flux during a short phase interval.
A **model** including two slightly misaligned accretion columns of different size with a simple **fan-beam** emission produces a pulse profile very similar to the one observed in KS 1947+300 based on the effect described above.

4U 1626−67

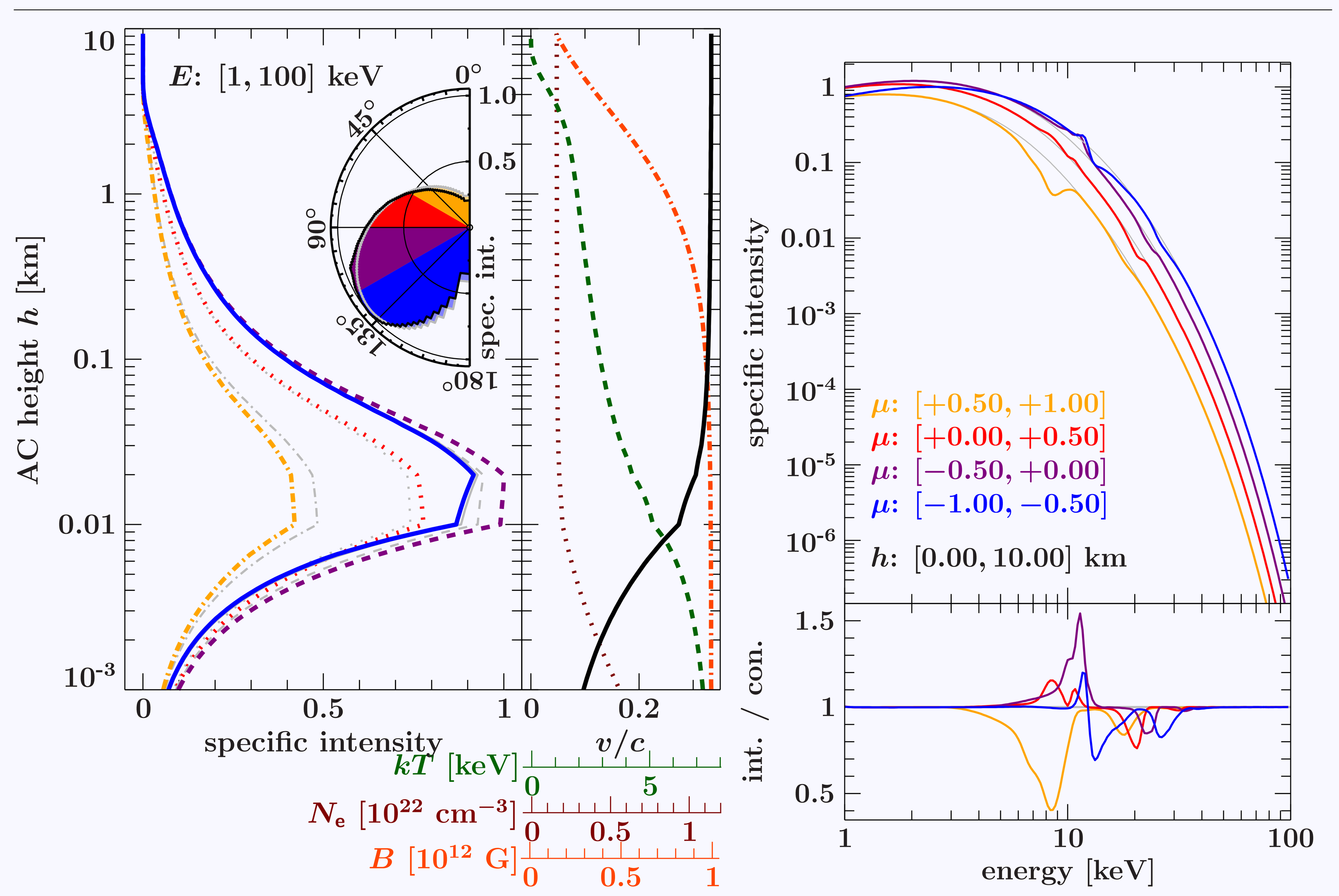


The **energy-resolved pulse profiles** of 4U 1626−67 (*NuSTAR*) evolve with increasing energy from a plateau-like shape with two narrow peaks close to each other to a broad single peak located at the plateau phase (Iwakiri et al., 2016).
The **model** involves two slightly asymmetric accretion columns emitting in both, **fan**- and **pencil**-beam. By only changing the relative contribution of the fan- and pencil-beam emission with energy (see polar plots) the model reproduces the data quite well at low and high energies. Note that all other parameters are fixed. At the intermediate energy there are some deviations, which may be resolved when allowing the fan- and pencil-beam properties (beam width & offset angle) also to change with energy.
Note that the effect of strong light bending (as in KS 1947+300) cannot explain these narrow double peaks, as they are too close to each other. Therefore, a pencil-beam like emission pattern is required to explain these peaks.

Physical Accretion Column Model



We are working on a self-consistent model to simulate the observed flux and pulse profiles of the accretion column(s) of a neutron star by combining three physical models. The thermal and bulk Comptonization model by Becker & Wolff (2007) (see also Wolff et al., 2016) as well as the simulations by Postnov et al. (2015) provide seed photon continua produced in the dense inner regions of the accretion column (AC). In a thin outer layer these seed continua are imprinted with cyclotron resonant scattering features (CRSFs) calculated using Monte Carlo simulations (Schwarm et al., 2016a,b). The light bending code described above then calculates the observed phase and energy dependent flux corresponding to these emission profiles.



Height and energy dependent emission profile of the physical AC model (using continua of Postnov et al., 2015).
Left: Height dependent, energy integrated emission of the AC in different emission angle bins ($\mu = \cos\theta$, with respect to magnetic field). The inlet shows the overall (height, energy integrated) beam pattern. The right panel shows the **bulk velocity**, **temperature**, **electron density** and **magnetic field strength** at the border of the AC.
Right: Upper and lower panels show the height integrated spectra and the ratio of these spectra to their corresponding continuum, respectively.

Acknowledgments & References

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Ballhausen, R., Kühnel, M., Pottschmidt, K., et al. 2016, 591, A65
Becker, P. A., & Wolff, M. T. 2007, ApJ, 654, 435
Iwakiri, W., et al. 2016, A&A, to be submitted
Postnov, K. A., Gornostaev, M. I., Klochkov, D., et al. 2015, MNRAS, 452, 1601
Schwarm, F.-W., Schoenherr, G., Falkner, S., et al. 2016a, A&A, in press (arXiv:1609.05030)
Schwarm, F.-W., Schoenherr, G., Falkner, S., et al. 2016b, A&A, to be submitted
Wolff, M. T., Becker, P. A., Gottlieb, A. M., et al. 2016, ArXiv e-prints

Summary

We present the application of our general relativistic ray-tracing code to **qualitatively reproduce** the (energy-resolved) **pulse profiles** of the two X-ray binaries, **KS 1947+300** and **4U 1626−67**, involving a simple asymmetric two column geometry with simple emission patterns.

Further we present our work on a **physical accretion column model** where we obtain the emission profile by processing the column's continuum emission simulated by Postnov et al. (2015) with the **cyclotron resonant scattering feature** code by Schwarm et al. (2016a,b).