Modelling the very high-energy γ-ray emission from accreting neutron stars in X-ray binaries: a theoretical framework for future observations

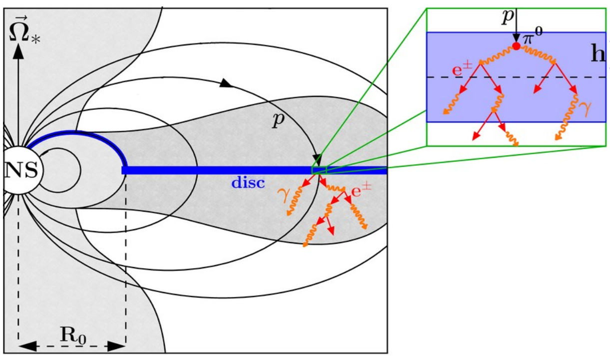
L. Ducci[1,2,3], P. Romano[3], S. Vercellone[3], A. Santangelo[1]

[1] Institut für Astronomie und Astrophysik, University of Tübingen, Germany; [2] ISDC Data Center for Astrophysics, Université de Genève, Versoix, Switzerland; [3] INAF – Osservatorio Astronomico di Brera, Via Bianchi 46, 23807 Merate, LC, Italy

Abstract

The search of γ-ray emission from accreting pulsars in X-ray binaries (XRBs) has been ongoing for some time. Recent marginal detections in high-mass X-ray binaries (HMXBs) have sparked renewed interest in this area. Anticipating future advances in γ-ray telescopes, we investigate the expected emission above 10 GeV from XRBs using an enhanced Cheng & Ruderman model. This model incorporates Monte Carlo simulations to account for cascade development inside and outside the accretion disc, including pair and photon production processes that involve interaction with nuclei, X-ray photons from the accretion disc, and the magnetic field. Our results yield a wide range of γ-ray luminosities (up to ~1E35 erg/s) and spectra, with some exhibiting emission below ~100 GeV and others extending to 10-100 TeV. We compare our findings with existing Fermi/LAT and VERITAS data for A0535+26 and GRO J1008-57, and look forward to more comprehensive comparisons with forthcoming, more sensitive instruments.

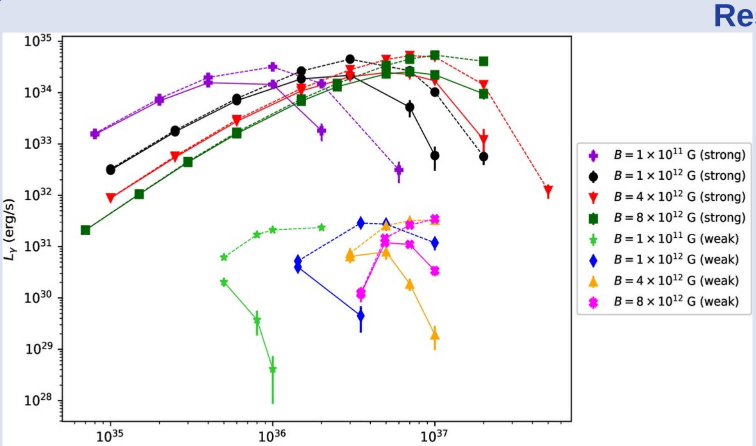
The model in a nutshell



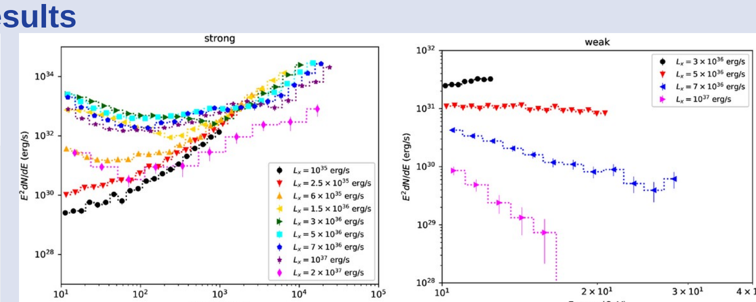
Schematic illustration of the model. Light grey regions corotate with the NS. Dark grey regions corotate with the accretion disc. A cone-like gap forms, where protons from the NS are accelerated toward the disc. Their interaction with it produce γ−ray primary photons via π^0 decay. In turn, primary photons develop cascades of $e^\pm$ pairs (red arrows) and other γ−ray photons (orange wavy arrows) inside the accretion disc and in the opposite side of it.

- Proton acceleration:
  - Strongly shielded gap (i.e.: no X-ray photons inside the accelerating gap);
  - Weakly shielded gap (or: pair production limited; i.e.: some X-ray photons in the gap; reduction of the potential drop across the gap);
- Primary γ−rays ($pp \rightarrow \pi^0 \rightarrow \gamma\gamma$): formalism by Aharonian & Atoyan (1996, 2000);
- Production of cascades:
  - Pair production in the Coulomb field of nucleus;
  - Pair production in the photon-photon collisions;
  - Magnetic pair production;
  - Bremsstrahlung;
  - Inverse Compton;
  - Synchrotron and curvature.
- Magnetically threaded disc and disc structure (Wang 1995; Shakura & Sunyaev 1973);
- Monte-Carlo simulations for the production of cascades;
- With this model, spectra are simulated above 10 GeV.

Results



γ -ray luminosities with respect to the input X-ray luminosity for different magnetic field strengths, strong and weak shielding, and for photons escaped from the disc (dashed lines) and photons that reached the observer (solid lines). The γ ray luminosity spans several orders of magnitude, with a maximum of ~10^{35}erg/s. It depends on the X-ray luminosity, the type of shielding, the magnetic field strength and spin period of the pulsar.



γ ray spectra of photons which reached the observer, for different luminosities and assuming strong and weak shielding. We find: 1. spectral variability vs input X-ray luminosity (and, similarly, vs input magnetic field strength; 2. softer spectra if the gap is weak shielded.

Comparison with detections and upper-limits

- detection of GRO J1008-57 (Fermi) and VERITAS upper-limits of A0535+26 (two accreting pulsars in high-mass X-ray binaries) are compatible with some of the solutions (especially for strongly shielded gap).

- more sensitive observations (CTA) required to effectively test the model.

For more details about the model: Ducci et al. 2023, MNRAS 525 3923 (arXiv: 2308.06061)

and contact me: ducci@astro.uni-tuebingen.de

For our study on the implications of a spatial coincidence between a gamma-ray source and the high-mass X-ray binary SAX J1324.4-6200 (Harvey et al. 2022), see: Ducci et al. 2024, A&A, 685, 148 (arXiv: 2403.01941)