Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
Proceedings IAU Symposium No. 363, 2023
E. Troja & M. G. Baring, eds.
doi:10.1017/S1743921322001041

Importance of electron-positron pairs on the maximum possible luminosity of the accretion columns in ULXs

Valery F. Suleimanov[1,2,3], Alexander Mushtukov[4,3], Igor Ognev[5], Victor A. Doroshenko[1,3] and Klaus Werner[1]

[1]Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, D-72076, Tübingen, Germany
email: suleimanov@astro.uni-tuebingen.de

[2]Kazan Federal University, Kremlevskaya 18, 420008 Kazan, Russia

[3]Space Research Institute of the Russian Academy of Science, Profsoyuznaya 84/32, 117997 Moscow, Russia

[4]Leiden Observatory, Leiden University, NL-2300RA Leiden, the Netherlands

[5]P. G. Demidov Yaroslavl State University, Sovietskaya 14, 150003 Yaroslavl, Russia

Abstract. One of the models explaining the high luminosity of pulsing ultra-luminous X-ray sources (pULXs) was suggested by Mushtukov et al. (2015). They showed that the accretion columns on the surfaces of highly magnetized neutron stars can be very luminous due to opacity reduction in the high magnetic field. However, a strong magnetic field leads also to amplification of the electron-positron pairs creation. Therefore, increasing of the electron and positron number densities compensates the cross-section reduction, and the electron scattering opacity does not decrease with the magnetic field magnification. As a result, the maximum possible luminosity of the accretion column does not increase with the magnetic field. It ranges between $10^{40} - 10^{41}$ erg s^{-1} depending only slightly on the magnetic field strength.

Keywords. accretion, accretion disks, stars: neutron, X-rays: binaries, radiative transfer

---

Introduction At present a few pULXs are known (see e.g. Fabrika et al. 2021). One of the models describing their observed high luminosities is a strongly magnetized neutron star (NS) with high mass-accretion rate (Mushtukov et al. 2015) in a binary system. This model predicts increasing of the pULX luminosity with the strength of magnetic field, and, therefore, NSs with a magnetar-like magnetic fields are necessary for explaining the observed pULX luminosities (see also Eksi et al. 2015; Brice et al. 2021). Here we improve the model by changing of some geometry assumptions and considering the contribution of electron-positron pairs to the opacity.

Model We made following improvements in the cross-section model of the accretion column. The magnetospheric radius $R_{\rm m}$ in radiation-dominated discs as well as the propeller conditions were computed according to Chashkina et al. (2019). We fixed the relative thickness of the transition layer between the disc and the magnetosphere $z_{\rm d} = \Delta R/R_{\rm m}$. We took into account the radiation friction between the radiation and the plasma outside the column. We changed the velocity law along the column height, $V(h) = V_0(h/H_{\rm x})^{\xi}$, where $\xi > 0$ is a parameter, and $H_{\rm x}$ is the current column height, $H_{\rm x=0} = H_0$. The dependence of the horizontal radiation flux was taken as $F(x) = F_0(1-\tau_{\rm x}/\tau_0)^{1/\beta}$ with a parameter $\beta \leq 1$. e^+ - e^- pairs were considered assuming thermodynamic equilibrium

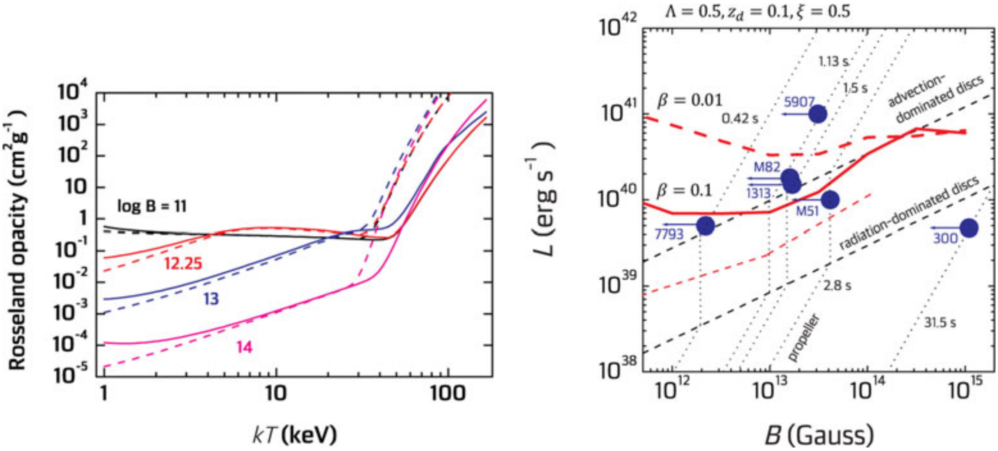

Figure 1. *Left panel:* Dependences of the Rosseland mean opacities on the plasma temperature for various magnetic field strengths and two plasma densities, ρ= 0.1 (dashed curves) and $10\,\mathrm{g\,cm^{-3}}$ (solid curves). The magnetic field strengths are marked at the curves. *Right panel:* Positions of the pULXs on the luminosity - NS magnetic field strength plane. The upper limits on the magnetic field strength are found from the propeller conditions. The corresponding conditions for five spin periods are shown with the dotted lines. The approximate boundaries for the magnetospheres located in the radiation- and the advection-dominated parts of the discs are also plotted with the dashed and the dot-dashed lines respectively. The new recomputed maximum possible luminosities of the accretion columns (with $H_0 = R_{\rm NS}$) are plotted with the thick solid (β=0.1) and dashed (β=0.01) red curves. The corresponding old curve (Mushtukov et al. 2015) is drawn with the thin dashed red curve.

according to Kaminker & Yakovlev (1993) and Mushtukov et al. (2019). It was shown in these papers that a number density of the pairs strongly depends on the magnetic field strength and increases significantly if $B > B_{\rm cr} = 4.414 \times 10^{13}$ G. We assume the solar H/He mix as a chemical composition of the accreting plasma, and take into account all the opacity sources namely free-free transitions, electron scattering, cyclotron absorption, opacity due to two-photon annihilation and one-photon annihilation in a strong magnetic field.

Results Electron scattering on e^+ - e^- pairs increases the Rosseland opacity at $kT > 30$ keV significantly (right panel in Fig. 1). We note that high luminosity accretion columns are optically thick at the considered parameters. Therefore, there are conditions for pair thermodynamical equilibrium and the pair numerical densities are significant along all the column height at high magnetic fields $B > B_{\rm cr}$. The opacity increase due to electron scattering on the pairs overcomes the opacity reduction due to magnetic field increase, and pairs prevent a huge luminosity of the accretion columns in magnetars at $B > 10^{14}$ G. (left panel in Fig. 1). The considered model provides the high enough accretion column luminosities at some parameters even at low magnetic fields, and strong NS fields are not necessary for pULXs even at low beaming due to the new propeller conditions derived by Chashkina et al. (2019).

References

Brice N., Zane S., Turolla R., Wu K., 2021, *MNRAS*, 504, 701
Chashkina A., Lipunova G., Abolmasov P., Poutanen J., 2019, A&A, 626, A18
Eksi K. Y., Andac I. C., Cikintoglu S., et al., 2015, *MNRAS*, 448, L40
Fabrika S. N., Atapin K. E., Vinokurov A. S., Sholukhova O. N., 2021, *Astroph. Bull.*, 76, 6
Kaminker A. D., Yakovlev D. G., 1993, *Soviet JETPh*, 76, 229
Mushtukov A. A., Ognev I. S., Nagirner D. I., 2019, *MNRAS*, 485, L131
Mushtukov A. A., Suleimanov V. F., Tsygankov S. S., Poutanen J., 2015, *MNRAS*, 454, 2539