Mass and radius of a neutron star as factors influencing the possibility of the appearance of radiation pressure-dominated shock above stellar surface at high mass accretion rates in X-ray pulsars

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Abstract

Astronomical objects classified as X-ray pulsars are strongly magnetised neutron stars in close binary systems. Material attracted from a companion star is accelerated in the gravitational field of a neutron star, and its kinetic energy is converted into heat and finally emitted in the X-ray energy band. The strong magnetic field of a neutron star shapes the geometry of accretion flow directing it towards small regions located close to the magnetic poles of a star. Misalignment between the magnetic and rotational axis of a neutron star results in periodic pulsations in X-rays. Observed pulse periods cover a wide range from milliseconds to several minutes. The magnetic field strength at the surface of a neutron star in X-ray pulsars is typically around 10^{12} Gauss, which is more than a trillion times stronger than the magnetic field strength observed at the Earth's surface and a million times above the maximal field strength achievable in terrestrial labs. Thus, neutron stars can be considered as the strongest magnets in the Universe.

Gas is accreted from the stellar companion and directed onto the magnetic poles of the neutron star by its magnetic field. This results in two or more localized X-ray hot spots. Before hitting the neutron star surface at these hotspots, the infalling gas can travel at a speed of half that of light. The infalling gas releases so much gravitational potential energy that hotspots, which are expected to be roughly one square kilometer in size, can be up to 10 thousand times as luminous as the Sun. Temperatures of millions of degrees are produced so the hotspots emit mostly X-rays. As the neutron star rotates, pulses of X-rays are observed as the hotspots move in and out of view if the magnetic axis is tilted with respect to the spin axis (Charles and Seward, 1995).

However, at high rates of mass accretion rates, the radiation pressure comes into play. Radiation pressure close to a neutron star's surface can be sufficient to stop accreting material at a radiation pressure-dominated shock above the stellar surface.

The parameters necessary for radiation pressure-dominated shock to manifest are still up for contention in the scientific community. Clarification of conditions required for the appearance of radiation pressure-dominated shock is necessary for the interpretation of the data from X-ray observatories including the IXPE polarimeter launched by NASA a year ago.

In our study, we examine the mass and radius of neutron stars as variables impacting the potential for radiation pressure-dominated shock to form at high mass accretion rates. We show that radiation-dominated shock is possible in the case of sufficiently large free-fall velocity at the neutron star's surface ($v>0.6c$). Otherwise, total deceleration of accreting material by X-ray radiation requires multiple oscillations of X-ray photons in between the neutron star's surface and accretion flow.

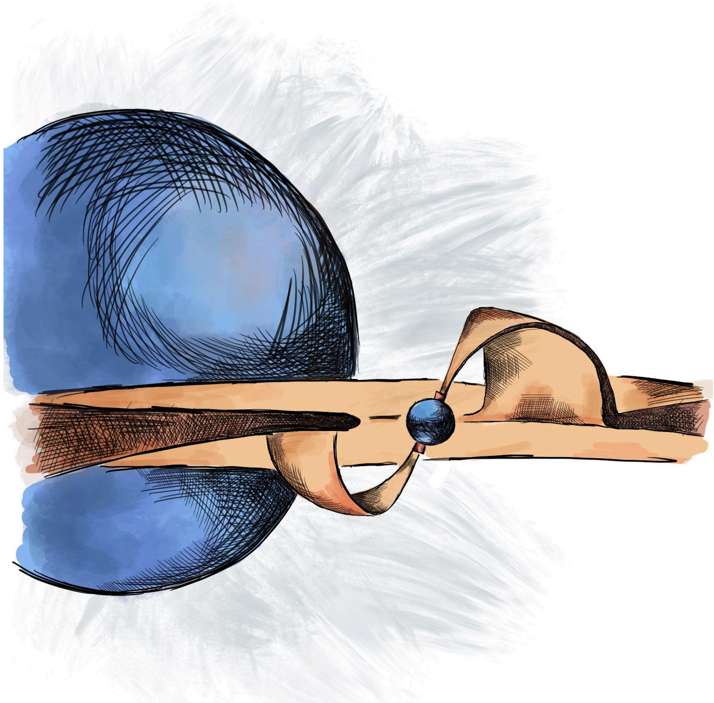

Figure 1. *Schematic view of accretion process in X-ray pulsars. Neutron star get material from its companion in a binary system and the material forms an accretion disc around a compact object. Accretion flow cannot come too close to a neutron star because of its strong magnetic field. Starting from the magnetospheric radius (about a hundred radii of a neutron star), accretion flow follows magnetic field lines and reaches the stellar surface in small regions located close to the magnetic poles of a neutron star.* ***Source Tsygankov et al, 2022***

Critical accretion onto neutron star surface

The mass and radius of a neutron star determine the free fall velocity of accreting material and its kinetic energy. The kinetic energy is transferred into heat and emitted in the form of X-rays. However, at high mass accretion rates, X-ray photons cannot leave the system freely: a fraction of X-ray radiation is scattered by the accretion flow above the neutron star surface. Compton scattering, which is the main process of interaction between radiation and matter under conditions of high temperatures expected in X-ray pulsars, results in momentum transfer from X-ray photons to the flow. If the momentum transfer is intensive enough, the interaction between radiation and flow leads to the deceleration of matter and, possibly, radiation pressure-dominated shock.

It is expected that radiation pressure-dominated shocks appear at mass accretion rates above 10^{17} g/s (Basko and Sunyaev, 1976). At higher mass accretion rates, one expects different geometry of the emission region - accretion columns supported by radiation pressure and confined by a strong magnetic field of a star (see Fig. 2). Different geometry of the emitting region results in a different beam pattern in X-rays (see Fig. 3). Variable mass accretion rate in transient X-ray pulsars can result in variations of a beam pattern and corresponding changes of a pulse profile (Gnedin & Sunyaev, 1973, see Fig. 4).

This provides an opportunity to detect changes in the geometry of the emitting region observationally. Observational evidence of changes in the geometry of the emitting region were already reported in a few X-ray pulsars: V0332+53 (Doroshenko et al., 2017), Swift J0243+6124 (Doroshenko et al., 2020, see Fig. 4), SMC X-3 and RX J0209-7427 (Liu et al., 2022), (Mushtukov et al., 2015)

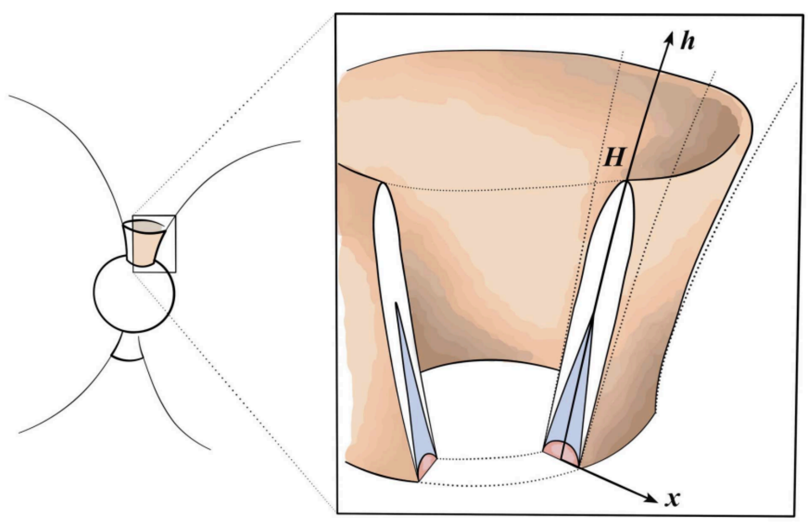

Figure 2. *Schematic illustration of accretion column above neutron star surface. The height of the column can be comparable to the neutron star's radius.*
Source: Mushtukov et al., 2018

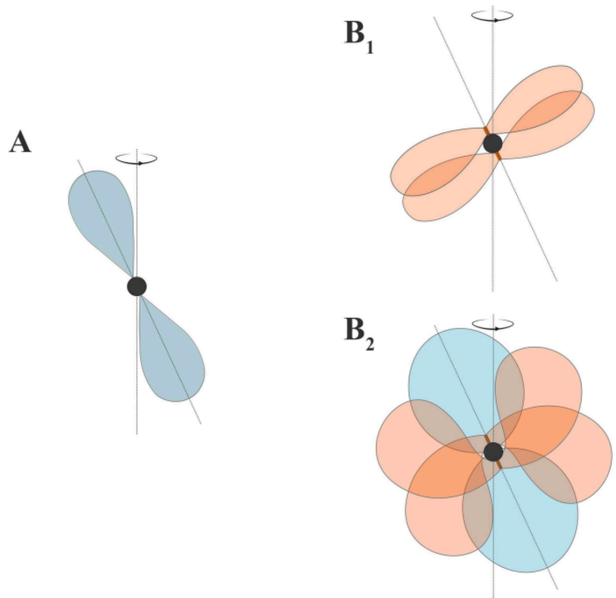

Figure 3. *Beaming of X-ray radiation from the neutron star in X-Ray pulsars at sub-critical mass accretion rates, when the accretion process results in hot spots at the neutron star's surface (A), and at super-critical mass accretion rates, when the accretion columns arise above the stellar surface (B_1 and B_2).In this case, the X-ray flux detected by a distant observer is composed of the direct radiation from the columns (red pieces of the beam pattern) and the radiation intercepted and reflected by the neutron star's atmosphere (blue pieces of the beam pattern).*
Source: Mushtukov & Tsygankov, 2021

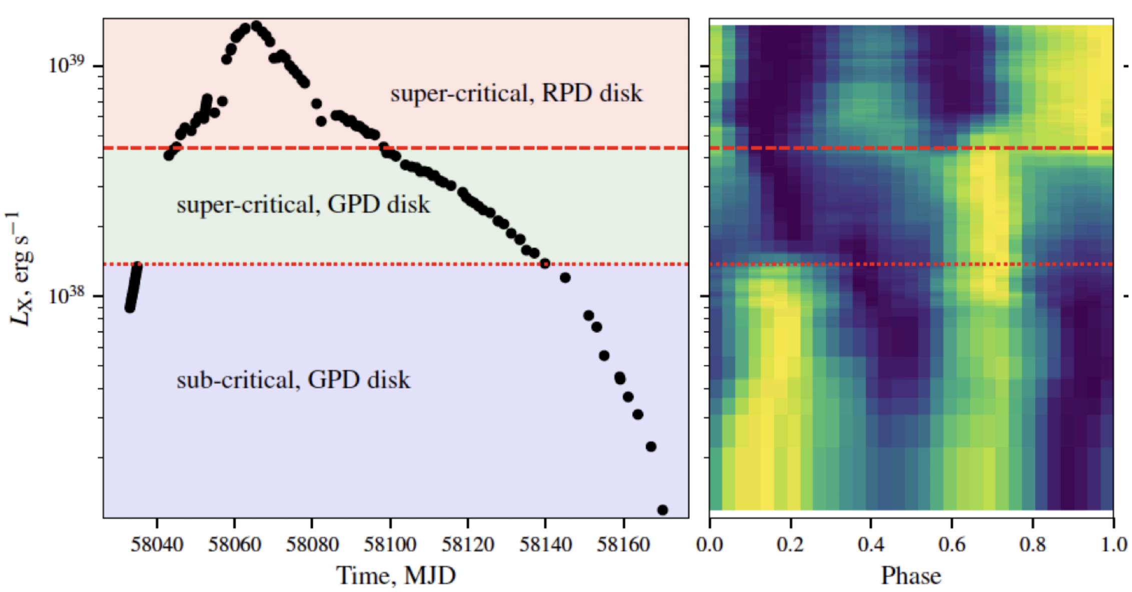

Figure 4. *Light curve of bright X-ray pulsar Swift J0243.6+6124 obtained during its 2017-2018 giant outburst with Insight-HXMT, NuSTAR, and Swift space observatories (left panel) and observed pulse*

profiles at different luminosity states (right panel). One can see that the pulse profile experiences changes with the luminosity. As it was discussed in the paper by Doroshenko et al., 2020, the changes in the pulse profile can be related to the appearance of radiation-dominated shock and accretion column above the neutron star surface.

Source: Doroshenko et al., 2020

Calculations of momentum transfer

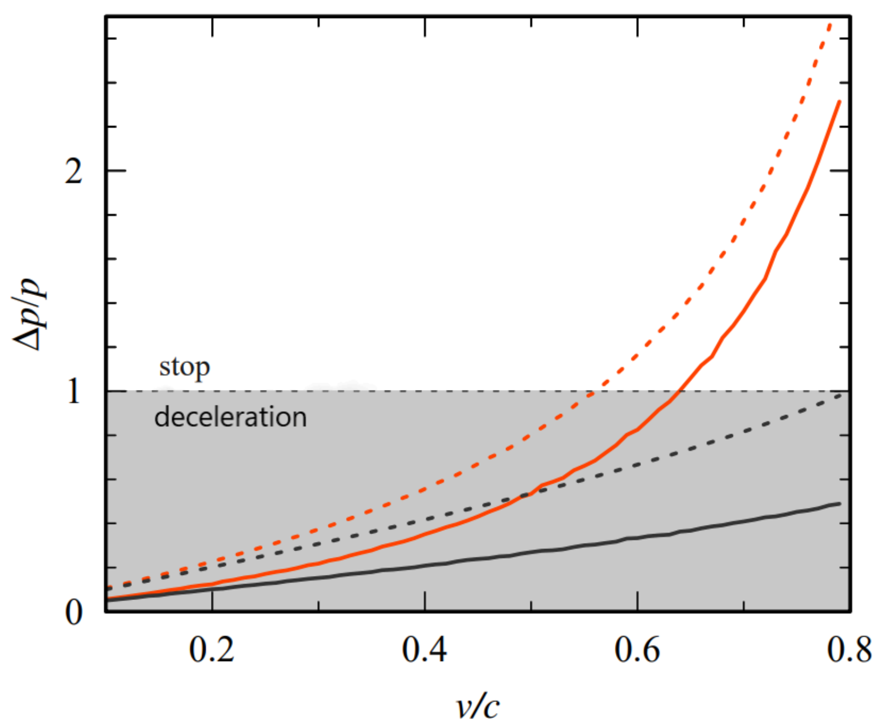

Figure 5. *The figure shows the efficiency of momentum transfer from X-ray photons to the accretion flow as a function of free fall velocity at the neutron star surface. Complete deceleration of the flow by radiation becomes possible in the case of ratio above unity. Black and red curves are given for non-relativistic and relativistic cases respectively. Dashed lines correspond to the case of scattering directed towards the neutron star surface only. Solid lines correspond to the case of isotropic scattering in the reference frame of accreting material. One can see that complete deceleration is almost impossible in the non-relativistic case (it requires free fall velocity above 0.8c). However, complete deceleration in non-relativistic case is possible, but it requires free-fall velocity above 0.6c in the case of isotropic scattering (see red solid line).*

In order to investigate the influence of mass and radius of a neutron star on the process of radiation shock formation, we have calculated the efficiency of momentum transfer from X-ray photons to the accretion flow, i.e. the ratio of momentum transferred to the accretion from X-ray photons Δp to the initial (before interaction with X-ray photons) momentum of accretion flow p (see Fig. 5). We have solved the problem in (i) non-relativistic approximation (represented by black lines in the above figure), and (ii) accounting for the effects of special relativity (represented by red lines in the above Fig. 5).

In our calculation we assumed that

(1) X-ray photons are produced by hot spots at the neutron star surface due to the accretion process and the total accretion luminosity is proportional to the mass accretion rate;

(2) most of the photons are intercepted by the accretion flow, which is a case at sufficiently high mass accretion rates;

(3) the scattering is isotropic in the reference frame of accreting material.

To solve the problem we have performed Monte Carlo simulations of X-ray photon's scattering by the accretion flow and prepared a code written in Python. Each run of the code includes 5000 photons.

We have demonstrated that in the non-relativistic case, a complete stop of accretion flow by radiative force in radiation-dominated shocks is possible only in the case of free-fall velocity above 0.8c (see black lines in Fig. 5), which is impossible in the case of neutron stars taking into account their equations of state proposed up-to-date (Nättilä and Kajava, 2022).

Accounting for special relativity makes the situation much better (see red lines in Fig. 4). In our model, we have taken into account the relativistic Doppler effect and relativistic aberration. The Doppler effect influences the relation between the photon energy in the reference frame of accreting matter and the reference frame of a neutron star surface. The relativistic aberration shapes the redistribution of X-ray photons over the directions after the scattering in the reference frame of a neutron star. In particular, the photons scattered isotropically in the reference frame of the accretion flow, tend to be beamed towards the stellar surface in the reference frame of a neutron star.

Both the Doppler effect and aberration make the process of momentum transfer more effective. Due to these effects, radiation pressure-dominated shock becomes possible at a free-fall velocity of about 0.6c already. A free-fall velocity of 0.6c is possible for some combination of neutron star mass and radius. However, the typical free-fall velocity is considered to be about 0.5c. In this case, the appearance of radiation pressure-dominated shock becomes possible in the case of multiple oscillations of X-ray photons in between the neutron star's surface and accretion flow.

Summary

We have considered bright X-ray pulsars and investigated the process of momentum transfer from X-ray photons to the accreting material. This problem is closely related to the process of formation of radiation-pressure dominated shock at supercritical regime of accretion (see, e.g., Basko&Sunyaev 1976, Mushtukov et al., 2015). We have developed a physical model and a Monte Carlo simulation code in Python. We have considered both non-relativistic and relativistic cases. It appears that in a non-relativistic case, momentum transfer is non-effective and material can hardly be stopped by radiation above the surface of a neutron star. However, accounting for relativistic effects (we have considered relativistic Doppler effect and aberration) makes the process of momentum transfer much more effective in comparison to the non-relativistic case.

The efficiency of the momentum transfer is still dependent on free-fall velocity and, therefore, neutron star mass and radius. For neutron stars with free fall velocity below 0.6c at the surface, single scattering of each photon is enough to stop the accretion flow. In the case of smaller free fall velocity, complete deceleration of the flow requires multiple oscillations of X-ray photons in between the accreting material and the neutron star's surface, which is possible only after taking into account the influence of the aberration and corresponding beaming of scattered photons towards neutron star's surface.

Our results show the importance of a neutron star's mass and radius in the calculation of the dynamics of accretion flow in bright X-ray pulsars and have to be taken into account in advanced models considering the formation of radiation-dominated shock.

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