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Radiation Pressure at The Upper Neutron Star Atmosphere In Super-Critical X-Ray Pulsars

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ABSTRACT

This paper shows the distribution of X-ray flux on neutron stars in super-critical X-ray pulsars to display the effects of varying accretion column heights on the material redistribution and atmospheric structure. This study calculates the flux distribution for different column heights and geometric configurations using a point source approximation for a neutron star being influenced by an accretion column. Our findings show that the distribution of X-ray flux depends on the column's height. In other words, larger columns lead to relatively lower homogenous distributions throughout the surface, whereas lower columns produce more complicated and diverse flux patterns. These variations point to considerable localized differences in temperature and density of the atmosphere, which may affect the X-ray spectra that the neuron star emits. Our follow trends set by earlier research on X-ray pulsars and show promising boundary applications to other high-energy astrophysical systems, including black hole binaries and active galactic nuclei, and are consistent with prior investigations of X-ray pulsars. Studies being done in the future should use more realistic geometries, magnetic field effects, and relativistic corrections. This is because the point source approximation does offer valuable insights, but does not fully depict the complexity of a real accretion column. Investigating the effects of variations in accretion rates on atmospheric dynamics and flux distribution is beneficial to improving upon this study. Contributing to our understanding of high-energy astrophysical environments, this work offers the foundation for developing models for X-ray flux distribution in accretion neutron stars.

Introduction

X-ray pulsars (XRPs) are accreting strongly magnetized neutron stars (NSs) in close binary systems. Magnetic field at the surface of an NS in these objects is expected to be ~1.e12 G and even stronger than that. Luminosity of XRPs covers more than 8 orders of magnitude from ~1.e33 erg/s and up to 1.e41 erg/s in the brightest objects. The vast majority of energy in XRPs is released in small regions located close to magnetic poles of an NS. It is expected that geometry of the emitting region in XRPs is dependent on the mass accretion rate and luminosity. At low luminosity, X-ray photons are emitted by hot spots, while at luminosity >1.e37 erg/s, radiative force at the NS surface is high enough to stop accreting material above the stellar surface in radiation dominated shock. In this case, formation of an accretion column is expected. Accretion columns are structures confined by the strong magnetic field of an NS and supported by radiation pressure. Luminosity emitted by accretion columns is fractionally intercepted by the compact objects. Thus, the atmosphere of an NS is illuminated by a source of X-ray photons located above the surface of a star. Because luminosity of an NS can exceed the Eddington limit, the external radiative force applied to the atmosphere of a star can be comparable to the local gravitational force, which should affect the structure of the atmosphere.

The compact object fractionally intercepts the brightness admitted by accretion columns. As a result, an X-ray photon source above the surface of a neutron star illuminates the star's atmosphere. The external radiative force acting on a star's atmosphere can be similar to the local gravitational force because neutron stars can be brighter than the Eddington limit. This should have an impact on the atmosphere's structure.

This study investigates the distribution of radiative pressure over the NS surface. The radiative force components along the NS surface and in the direction orthogonal to the atmosphere will be considered. The component along the surface should influence redistribution of atmospheric material over the stellar surface, while the radiative force in the direction orthogonal to the surface should affect vertical stricture of the atmosphere. The scope of this paper is confined by a case of point source above the stellar surface, but consider both cases of flat and curved space in close proximity to the NS surface.

Model Set Up

To estimate the radiative force applied to the atmospheres of accreting neutron stars from accretion columns, the flux distribution over the surface of a neutron star is calculated. This study neglects the effect of light deflection in space curved by an NS and limits ourselves by the solution in flat space-time. In this cases, some results can be obtained analytically. Instead of an extended source of radiation a point source of a given luminosity L is considered. This approximation is reasonable because accretion flow undergoes radiation dominated shock at the top of accretion column and in the case of accretion column of height H<R, the most of energy is emitted there.

The distribution of X-ray energy flux over the surface of an NS is dependent on luminosity of a point source and its location in space, i.e. height above NS surface. The flux can be calculated as

$$F = \frac{L\ \sin\ \alpha}{4\pi R^2 \sin\ \theta}\left(\frac{d\alpha}{d\theta}\right)$$

where

$$\sin\alpha = \frac{R \sin\theta}{R^2 + (R+H)^2 - 2R(R+H)\cos\theta}$$

determines direction of photon momentum and

$$\frac{d\alpha}{d\theta} = \left(\frac{(R+H)\cos\alpha}{\sqrt{R^2 - \sin^2\alpha\,(R+H)^2}} - 1\right)^{-1},$$

L is the luminosity of the accretion column, R is the radius of an NS, and a and θ is the co-latitude at the stellar surface.

Several analytical approaches and numerical simulations were applied to do these computations. The derived equations were used in Python code to calculate the radiative flux distribution for both different luminosities as well as different geometric configurations (heights of a point source above NS surface). Considering the accretion column's features such as its height and the neutron star's shape, the formulas listed above were derived analytically. Using them, the radiative pressure distribution across the neutron star's surface was calculated. To create the three figures used in this study, Matplotlib and other libraries within Python were used as well as computations, numerical simulations, and estimations.

Results

Calculating X-ray energy flux distribution over the NS surface, a comparison is made between our results and the local Eddington flux:

$$F_{Edd} = \frac{2 \times 10^{38} erg/s}{4\pi R^2} = 1.6 \times 10^{25}\ erg\ s^{-1} cm^{-2}$$

At the Eddington flux, the radiative force becomes comparable to the gravitational force and, thus, radiation can influence the structure of the atmosphere. As one can see, the flux at any point at the NS surface is linearly proportional to accretion luminosity. Keeping that in mind, it is important to consider the specific accretion luminosity $L_{acc} = 10^{39}$ erg/s, which has been detected in a few bright X-ray pulsars and ultra-luminous X-ray sources powered by accretion onto an NS.

The computed X-ray radiation flux distributions are presented in Fig. 1 and 2. Each of these plots show the variation of the radiative flux as a function of co-latitude at the NS surface.

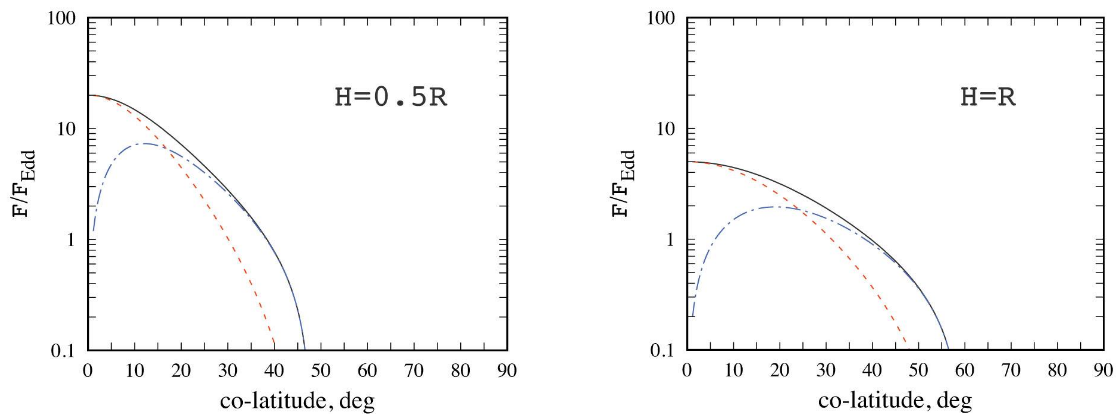

Figure 1. X-ray flux distribution over the surface of an NS. Black solid line illustrates the total flux, while red dashed and blue dashed-dotted lines show the components of X-ray flux along the normal to the stellar surface and along the surface of an NS. Left and right plots are given for different height of a point source above NS surface: H=0.5R and H=R respectively.

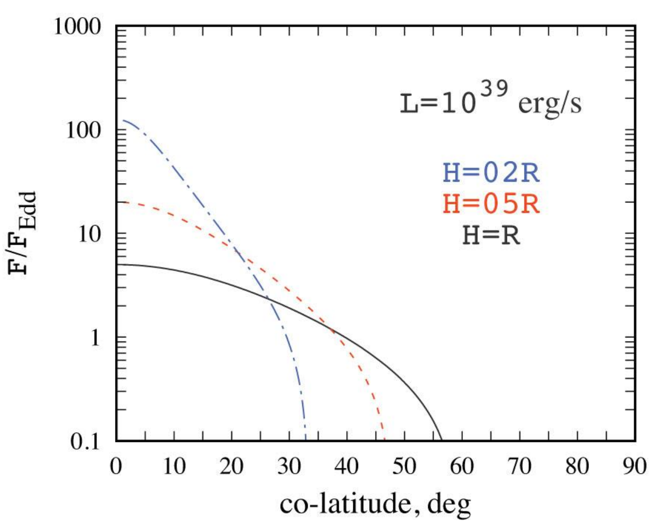

Figure 2. X-ray flux distribution over the surface of an NS. The luminosity of a point source is fixed at $10^{39}\mathrm{erg/s}$. Different curves are given for different heights of a point source above NS surface: 0.2R (blue dashed-dotted), 0.5R (red dashed) and R (black solid).

The radiative flux distribution for a column with a height (H) of 0.5R and R is shown in Fig.1. Fig.1 shows decomposition of the flux into two components: the component orthogonal (dashed lines) to the stellar surface and the component along the surface of an NS (dashed-dotted lines). Both components drop towards the equator of an NS. The component along the NS surface turns to zero at the magnetic pole of an NS as well. Flux that illuminates NS surface is scaled with the luminosity of an object located above the surface and in the case of sufficiently large accretion luminosity, the both components of X-ray energy flux can exceed local Eddington limit.

The radiative flux distributions for various column heights of 0.2R, 0.5R, and R are shown in Fig.2. Higher sources of X-ray radiation can illuminate a larger fraction of stellar surface. At the same time the total flux right below the source of radiation tends to be larger in the case of larger height.

The distribution of radiative forces with a column height of H = R is shown in Figure 1. There are notable differences in the forces' distribution, with stronger forces focused at specific angular positions. This distribution emphasizes even further the effect of column height on the radiative force operating on the surface of the neutron star. Pronounced peaks in the force distribution for H = R imply that the overall structure and stability of the atmosphere may be layered by large displacement or compression of the atmospheric material in discrete locations.

Even though the component along the neutron star's surface focuses on the redistribution of atmospheric material, the radiative force component orthogonal to the surface actually affects the atmosphere's vertical structure. An important structural change in the star's atmosphere could result from the radiative force being comparable to the local gravitational force, which can be seen in the analysis.

In areas with weaker radiative forces, there could be an increase in material build up. Meanwhile, in areas with stronger radiative forces, atmospheric density would decrease. Due to this dynamic redistribution, the temperature and density profiles of the neutron star's atmosphere may change, potentially affecting the released X-ray spectra. Figures 1 and 2 show the various force distributions that show how the form and height of the accretion column with the underlying magnetic field structure will have a major effect on the atmospheric reaction.

The visible features of accreting neutron stars are directly affected by variations in the radiative force distribution. For example, variations in the density and structure of the atmosphere might impact the neutron star's x-ray luminosity and spectrum. Because of greater energy deposition, areas with higher radiative forces may exhibit enhanced X-ray emission, whereas areas with lower radiative forces may exhibit reduced X-ray emission. Additionally, time-dependent variations in the measured X-ray characteristics may result from the dynamic redistribution of atmospheric material.

Variations in radiative focus resulting from variations in the accretion rate column height can manifest as variations in X-ray light curves and spectra. The physical circumstances and processes taking place close to the neutron star can be inferred from these observable signals.

Discussion

The neutron star's atmosphere may be pushed by the radiative force from the accretion column, which might cause material to be redistributed and alter the atmosphere's overall structure. This force is especially relevant in extremely Super-Eddington luminosity systems. The results align with the theoretical expectations proposed by Basko and Sunyaev (1976), who postulated that radiative shocks over a certain brightness might impact the dynamics of the surrounding atmosphere and the accretion column (Basko & Sunyaev, 1976). Such high fluxes have the ability to dramatically affect the neutron star's thermal and dynamic equilibrium, which may result in detectable alterations in the X-ray spectra that are released.

Understanding the physics of these extreme environments is mainly reliant on the research into radiative forces in accreting neutron stars. The X-ray flix, which determines the overall parameters of the accretion process, might affect the accretion columns' stability and structure (Mushtukov, Nagirner, & Poutanen, 2015). Understanding this can help us better understand high-energy astrophysical events by providing insights into how XRPs and other compact objects form.

Our results agree with those of Mustukov et al. (2015), who demonstrated that large radiative forces are present in accreting neutron star systems. Although our focus is on flux distribution, the ramifications of these forces are also related to the behavior of in-falling material and its interaction with the star's atmosphere, as Mushtukov et al. (2015) point out (Mushtukov et al., 2015). Furthermore, the recent paper by Kylafis et al. (2021) is significant to our discussion of X-ray flux distribution because it gives a complete examination of cyclotron line creation in the radiative shock, emphasizing the importance of Doppler boosting and the subsequent shifts in spectral characteristics (Kylafis et al., 2021).

The results of this study have wider implications regarding our understanding of accretion mechanisms in other high-energy astrophysical events like active galactic nuclei (AGN) and black hole binaries. These systems, where similar processes may occur on a bigger scale, can benefit from the use of X-ray flux principles and their effects on accreting material (Tsygankov et al., 2017; Doroshenko et al., 2017). This is why a unified knowledge of accretion processes across many astrophysical environments can benefit from the study of X-ray flux distribution.

Additionally, this study can help create more advanced models and simulations for future research. Better models can help interpret data from existing and upcoming X-ray observatories by improving predictions of observational signatures.

This work does not take into account more intricate geometries of the accretion column and is restricted to the point source approximation. Subsequent research in this area should expand the analysis to more realistic models and include relativistic corrections and the effects of magnetic fields, because magnetic fields play an important role in determining the interaction between radiation and matter in highly magnetized neutron stars (Camero-Arranz et al., 2012). To give a more thorough understanding, for example, future models may incorporate the work of Poutanen et al. (2013) on cyclotron line reflection models and their implications for magnetic field measurements (Poutanen et al., 2013). Furthermore, because these parameters have the potential to dramatically change the accretion dynamics and consequent forces, it is important to investigate how magnetic field topology and strength affect the X-ray flux distribution.

The fluctuation of the accretion rate and its effect on the X-ray flux distribution should be taken into account in further research. Changes in accretion rates can cause large fluctuations in luminosity, which in turn affects the atmospheric dynamics (the distribution of Swift and NuSTAR will be crucial for deciphering the observational signatures of XRPs and their atmospheric responses). This is demonstrated by the extensive observational data from Swift and NuSTAR on sources such as Cen X-3 (Swift and NuSTAR observations, 2021).

Also, research is necessary to determine the possible influence of X-ray flux on the long-term evolution of neutron star atmospheres. Continuous high flux may cause the composition and structure of the atmosphere to gradually alter, which over time will affect the neutron star's thermal and spectral properties. Long-term observational programs of accreting neutron stars can yield important information validating these theoretical forecasts and improving our models.

Summary

This study has investigated the process of neutron star illumination by a point source located above the stellar surface. This situation is expected in bright super-critical X-ray pulsars - accreting strongly magnetized neutron stars.

Through the consideration of different column heights and geometric configurations, this study has demonstrated that the atmospheric structure and material distribution on the surface of the neutron star can be greatly impacted by the X-ray flux. According to our findings, the radiative force may be similar to the local gravitational force, which might cause a dynamic redistribution of atmospheric material and have an impact on the X-ray spectra that are released. Figures 1 and 2's uniform and complex radiative force distributions emphasize how crucial column height and spatial curvature are in determining the atmospheric response. These results have immediate consequences for deciphering X-ray observational data and comprehending the physical conditions in XRPs.

Understanding the physical conditions in XRPs and interpreting observational data from X-ray telescopes are directly affected by these results.

Even with the improvements that were made, there are still limitations to our work. For one, the point source approximation is not able to capture the entire complexity of the actual accretion column despite its helpfulness to this study. To ensure proper advancement in this research, future studies should aim to include the corrections that match with any improvements/changes made to the study, magnetic field effects, and geometries that are more realistic. In short, more research is required to determine how variations in accretion rates affect the distribution of radiative forces.

All things considered, this study lays the groundwork for further investigations into radiative forces in high-energy astrophysical environments. Our comprehension of the most extreme occurrences in the universe can be advanced by gaining a greater grasp of the intricate dynamics of accreting neutron stars and other compact objects through the improvement of our theoretical models and the implementation of long-term observational efforts.

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