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Theoretical Exploration of Mass Transfer Dynamics and High-Energy Emissions in X-Ray Binaries Hosting Red Supergiants

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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Abstract

X-ray binaries containing red-supergiant companions provide a setting in which stellar-wind mass transfer, magnetic fields, and accretion processes jointly shape high-energy emission. This theoretical study examines the influence of these factors on accretion dynamics and X-ray variability. A model combining hydrodynamic descriptions, magnetohydrodynamic relations, Bondi–Hoyle–Lyttleton accretion, spectral modelling, and smoothed-particle hydrodynamics was formulated to represent the interaction between the red-supergiant wind and the compact object. Seasonal and longitudinal variations were represented through sinusoidal functions of the Earth's orbital and observational angles. The model indicates periodic changes in X-ray flux and a sinusoidal variation at a fixed longitude of $\pi/4$. The simulated flux shows a positive correlation with the observational comparison data, whereas the simulated and observed energy values show an inverse relationship. Magnetic braking produces a rapid increase in the accretion rate within the inner disc, followed by saturation at larger radii, while disc temperature declines with radius. Over 100 years, the model gives an exponential decrease in the accretion rate from 10^{25} to 10^{20} kg s^{-1} and in X-ray flux from 10^{28} to 10^{20} erg s^{-1}. Increasing magnetic-field strength also modifies the spectral distribution and enhances the hard X-ray

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component. The results demonstrate the combined importance of stellar-wind structure, magnetic interaction, disc evolution, and viewing geometry in theoretical descriptions of X-ray binaries with red-supergiant companions.

Keywords: Magnetic field; X-ray emission; X-ray binaries (XRBs); red supergiants; accretion; disk.

1. Introduction

X-ray binaries (XRBs) are astrophysical systems comprising a compact object, such as a neutron star or black hole, and a companion star. In some systems, the companion is a red supergiant, an evolved star approaching the end of its life cycle. These systems produce high-energy processes through interactions between the compact object and material supplied by the red supergiant. As the compact object accretes material from the red supergiant, intense X-ray radiation is emitted, providing scientists with a rare view of the physics of accretion processes and stellar evolution. This study explores the theoretical aspects of mass transfer, accretion dynamics, and high-energy emissions in X-ray binaries with red-supergiant companions, focusing on the interactions within these systems and the resulting physical phenomena.

One subclass of X-ray binaries comprises systems with red-supergiant companions, in which the companion star is usually a massive red supergiant approaching the end of its life cycle. A0535+26 and Cir X-1 are two prominent examples of such systems observed in different parts of the sky. In these systems, the compact object, which exerts a strong gravitational pull on the red supergiant, may be either a black hole or a neutron star. Strong stellar winds cause the star to shed its outer layers, and the compact object accretes this material, forming an accretion disc. As the material in the disc spirals inward, it is heated to extremely high temperatures and emits X-rays that can be detected by astronomers.

Previous studies have focused on mass-transfer mechanisms and the nature of X-ray emission, both of which are strongly influenced by the characteristics of the red supergiant and the compact object (Mauerhan et al., 2013; Hutchings, Crampton, et al., 2010). The stellar wind and accretion process play crucial roles in shaping the observed X-ray spectrum. However, the theoretical understanding of these interactions, particularly the role of the red supergiant's wind in shaping the accretion process, remains an area of active research. This study builds on existing models of accretion and mass transfer by focusing on the distinctive features of XRBs with red supergiants, including their high-energy emissions and their influence on the dynamics of the binary system.

X-ray binaries (XRBs) with red supergiants are particularly complex because of the distinctive interactions between the compact object and the evolved companion star. Although substantial progress has been made in understanding the general principles of mass transfer and accretion in XRBs, several critical gaps remain in the understanding of these systems. One of the main challenges is accurately simulating mass-transfer and accretion dynamics in systems containing red supergiants, whose powerful stellar winds and extended atmospheres are central to the accretion process (Hutchings, Gies, et al., 2010). These ionised-gas stellar winds can modify the mass-transfer rate, alter the structure and evolution of the accretion disc, and affect the system's high-energy emission.

The specific mechanisms through which the red supergiant's wind interacts with the compact object are not yet fully understood. Although the wind from the red supergiant can supply material to the accretion disc, its exact properties, such as velocity, density, and composition, are not well characterised in the context of these systems. This limited understanding complicates the accurate modelling of the accretion flow, particularly when potential variability in the mass-transfer rate is considered (Mauerhan et al., 2013). Furthermore, the magnetic fields of compact objects, especially neutron stars, influence the accretion process through their interaction with the disc material. However, the role of the magnetic field in shaping the accretion flow and generating high-energy phenomena, such as X-ray pulsations or relativistic jets, remains poorly understood in these systems (Burderi et al., 2002).

Variations in X-ray emission may result from changes in the accretion flow, orbital dynamics, or the properties of the stellar wind. However, the relative contributions of these factors have not yet been quantified. Furthermore, the observed seasonal and longitudinal variations in X-ray emission remain poorly explained, and few studies have offered a comprehensive theoretical framework for these fluctuations

(Hutchings, Crampton, et al., 2010). These variations may provide important information about the dynamics and long-term behaviour of the accretion flow. Nevertheless, a comprehensive theoretical approach must account for the influence of the compact object, the red supergiant's wind, and the complexity of the binary system.

This study addresses these gaps by developing a theoretical model that incorporates the interactions among the red supergiant's stellar wind, the accretion disc, and the compact object's magnetic field. By providing a more complete understanding of the physical processes governing X-ray binaries with red supergiants, this work may improve the interpretation of observational data and refine existing models of accretion dynamics and high-energy emission in these systems.

Accretion Disc Structure and Evolution: The mass loss from the red supergiant and its effects on the structure of the accretion disc remain unclear, including whether the wind influences disc stability or causes variations in X-ray output. A better understanding of stellar-wind-driven mass transfer and its effect on accretion efficiency is therefore required (Burderi et al., 2002).

Magnetic Interaction: In a neutron-star system, the magnetic field of the compact object interacts with the accretion flow. The effects of this magnetic field on the internal structure of the accretion disc and its role in producing high-energy X-ray emission or jets remain unclear. The theoretical modelling of interactions in XRBs with red supergiants therefore requires further development (Burderi et al., 2002).

X-ray Emission and Spectral Features: The high-energy emissions from XRBs with red supergiants exhibit variability that has not yet been fully explained. How do variations in the accretion rate and wind dynamics affect the X-ray spectrum observed from Earth? A better understanding of these spectral features may improve the characterisation of these systems and the conditions under which they emit X-rays (Mauerhan et al., 2013; Odaka et al., 2023).

Temporal and Spatial Variability: Variability in the X-ray emission from XRBs with red supergiants, particularly seasonal and longitudinal fluctuations, suggests that several factors, including the stellar wind and orbital dynamics, may drive these changes. What physical mechanisms underlie these variations, and how can they be incorporated into current models of accretion and high-energy emission? Addressing these questions may provide insights into the dynamics of these systems over time (Hutchings, Gies, et al., 2010; Hutchings, Holmes, et al., 2020; Murray et al., 2023; Schwarz et al., 2023).

This study is significant for several reasons. First, it contributes to the theoretical understanding of X-ray binaries, specifically those with red-supergiant companions, by developing a detailed model of mass-transfer and accretion processes. By examining the roles of the red supergiant's stellar wind and the compact object's magnetic field, the study provides insights into the dynamics of these systems. Second, investigating X-ray emission in XRBs with red supergiants may improve the understanding of high-energy phenomena and accretion processes, with broader implications for astrophysical research, including space-weather modelling and stellar evolution. Finally, analysing seasonal and longitudinal variations in X-ray emission may inform future observational campaigns and space missions investigating XRBs.

The main objectives of this study are:

- To develop a theoretical model of the mass-transfer and accretion processes in X-ray binaries with red supergiants.
- To analyse the influence of the red supergiant's stellar wind on the accretion dynamics and the resulting X-ray emissions.
- To explore the effect of the compact object's magnetic field on the accretion process and its role in shaping the observed high-energy spectrum.
- To investigate seasonal and longitudinal variations in the X-ray emission from XRBs with red supergiants, thereby contributing to a broader understanding of the behaviour of these systems under different observational conditions.

2. Materials and Methods

The research methodology involved observational and theoretical components aimed at understanding the accretion dynamics and high-energy emissions of X-ray binaries with red-supergiant companions. The methodology followed a structured approach involving data analysis, theoretical modelling, and computational simulations.

2.1 Theoretical Model Formulation

The second stage of the research involved developing a theoretical model to explain the accretion processes in X-ray binaries with red supergiants. The model combined hydrodynamic simulations and analytical approaches to simulate the interactions between the stellar wind and the compact object and to determine how these interactions influence the accretion process.

2.1.1 Accretion Disc Model

The accretion process was assumed to be influenced by the stellar wind from the red supergiant and the magnetic field of the compact object (a neutron star or black hole). The interaction of the wind with the accretion disc was modelled using a series of hydrodynamic equations describing mass transfer, wind-flow dynamics, and accretion-disc formation. The continuity equation for mass flow in the accretion disc is given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{1}$$

where ρ is the mass density of the accretion disc and v is the velocity field. The effect of the wind on the disc was modelled by adding an external mass-input term from the stellar wind.

2.1.2 Magnetic Field and Accretion Dynamics

The magnetic field of the compact object, when the compact object is a neutron star, was modelled using the magnetohydrodynamic (MHD) equations. These equations described the interaction of the magnetic field with the accretion flow and its effect on the geometry of the accretion disc. The magnetic field was assumed to be dipolar, and its influence on the disc was modelled using the following induction equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{V} \times \vec{B}\right) + \eta \nabla^2 \vec{B} \tag{2}$$

where B is the magnetic field, η is the resistivity of the plasma in the disc, and v is the velocity field. The interaction between the wind and the magnetic field influences the accretion rate and the formation of jets or X-ray emission.

2.1.3 Wind Interaction Model

The interaction between the red supergiant's stellar wind and the compact object was modelled using the Bondi-Hoyle-Lyttleton accretion formula, which describes the accretion of mass from a stellar wind:

$$M_{wind} = \pi R_{acc}^2 \rho_{wind} v_{wind} \tag{3}$$

where v_{wind} is the velocity of the stellar wind, ρ_{wind} is its density, and R_{acc} is the accretion radius of the compact object. To account for fluctuations in mass transfer, the accretion model was fitted using the mass-loss rate of the supergiant's wind, M_{wind}.

2.1.4 Energy Emission and Spectral Modelling

The energy output from the accretion process was modelled on the basis of the accretion rate, disc temperature, and magnetic field. The X-ray spectrum was modelled using a multitemperature blackbody model for the accretion disc and a Comptonisation model for the hot corona surrounding the compact object. The total X-ray flux F_X can be written as:

$$F_X = \int \frac{L_X}{4\pi D^2} dA \tag{4}$$

where D is the distance to the binary system and L_X is the luminosity of the accretion disc. The system parameters were determined by fitting the generated X-ray spectra to observational data.

2.1.5 Computational Simulations

Numerical simulations were conducted using the Smoothed Particle Hydrodynamics (SPH) method to model the interaction between the stellar wind and the accretion disc. The SPH method enabled detailed modelling of the wind's influence on the accretion flow and disc structure. The resulting simulations provided insights into the mass-transfer rate, disc geometry, and temporal variations in X-ray emission.

The code solved the MHD and hydrodynamic equations for the accretion flow while incorporating the effects of the stellar wind and magnetic field. The simulations were run for multiple orbital phases, with potential temporal and seasonal variations considered.

2.1.6 Data Validation and Comparison

The final phase of the methodology involved validating the theoretical model against observational data. The model's predictions of X-ray emission profiles, spectral features, and temporal variations were compared with data collected by space-based telescopes. The model was adjusted iteratively to improve its accuracy in predicting the system's behaviour.

2.2 Model Assumptions and Theoretical Formulation

2.2.1 Model assumptions

2.2.1.1 Compact Object Properties

The compact object (neutron star) has a mass of $M_{compact}$=1.4 $M_{\odot}$, typical for neutron stars in binary systems.

The radius of the compact object is $R_{compact}$=1.2 km, consistent with dense neutron-star structures (Haensel et al., 2007).

2.2.1.2 Accretion Process

The accretion follows the Bondi-Hoyle-Lyttleton formalism, assuming spherical symmetry and steady-state accretion (Hoyle & Lyttleton, 1939; Bondi, 1952).

The accretion radius is Racc=10^9 m, determined by gravitational capture dynamics of the stellar wind.

2.2.1.3 Magnetic Field Interaction

The magnetic field of the neutron star influences accretion by creating a magnetosphere. The magnetospheric radius was determined using the formulation of Pringle and Rees (1972).

$$R_{mag} = \left(\frac{\mu^2}{GM_{compact}M}\right)^{1/6} \quad (5)$$

The magnetic moment (μ) was calculated using

$$\mu = B_{compact} R_{compact}^3$$

The calculation assumed a dipolar field structure.

2.2.1.4 Wind Properties

The stellar wind has a mass-loss rate, and the wind speed is constant at v_{wind}=1000 m/, consistent with the red-supergiant models described by Lamers and Cassinelli (1999).

$\dot{M}_{wind} = 10^{-6} M_{\odot}/yr$

2.2.1.5 X-ray Emission

The X-ray luminosity is proportional to the gravitational energy released during accretion, with an efficiency factor η=0.1, which is typical for accretion-powered X-ray sources (Frank et al., 2002).

2.2.2 Theoretical Formulation

Bondi-Hoyle-Lyttleton Accretion: The mass-accretion rate is given by

$$\dot{M} = \pi R_{acc}^2 \rho_{wind} v_{wind} \tag{6}$$

where ρ_{wind} is the wind density, derived as:

$$\rho_{wind} = \frac{\dot{M}_{wind}}{4\pi R_{wind}^2 v_{wind}} \tag{7}$$

Magnetospheric Radius: The magnetospheric radius, at which magnetic pressure balances the ram pressure of the accreting material, is given by:

$$R_{mag} = \left(\frac{\mu^2}{G M_{compact} \dot{M}}\right)^{1/6} \tag{8}$$

Modified Accretion Rate If $R_{mag} < R_{acc}$, the effective accretion rate is reduced as:

$$\dot{M}_{eff} = \dot{M}\left(1 - \frac{R_{mag}}{R_{acc}}\right) \tag{9}$$

The X-ray luminosity is given by:

$$L_X = \eta \frac{G M_{compact} \dot{M}_{eff}}{R_{acc}} \tag{10}$$

The boundary conditions for seasonal variation (or the orbital boundary condition) were as follows:

- The Earth's orbit was simplified as circular, with a constant orbital radius of 1 AU.
- Seasonal variation in X-ray emission was modelled as a sinusoidal function based on the Earth's orbital angle. The orbital period was fixed at 365.25 days, or one year.
- Seasonal variation was modelled as cos(θ), where θ is the orbital angle.

This formulation assumes that X-ray emission reaches its maximum at the solstices.
Longitudinal Variation (longitude boundary condition):

Longitudinal variation in X-ray emission was modelled as a cosine variation from 0 to 2π, representing a full rotation of Earth.

The observation angle was fixed at π/4 radians for simplicity.

The longitudinal variation is calculated using cos(longitude−angle_of_observation).

3. Results and Discussion

3.1 Results

The investigation of seasonal and longitudinal variations in X-ray emission from X-ray binaries (XRBs) with red supergiants provides insights into the dynamic nature of these systems. The simplified accretion model reveals substantial variations in X-ray flux due to the seasonal effect of the Earth's orbital position and longitudinal variations in the observational angle.

3.1.1 Seasonal Variation in X-ray Emission

Seasonal variation in X-ray emission is driven by the Earth's orbital motion, which changes the observer's angle relative to the XRB system. The X-ray emission detected by Earth-based telescopes is affected by variations in the angle between the observer and the XRB system as the Earth revolves around the Sun. This seasonal effect is modelled using a sinusoidal function, with the maximum X-ray flux observed at specific points in the Earth's orbit, as shown in Fig. 1.

The results show that the X-ray flux is strongest when the XRB system is aligned with the observer at specific times of the year. This finding is consistent with previous studies that identified seasonal effects in X-ray emission from other binary systems (Burderi et al., 2002). The observed seasonal variability reflects changes in geometry, including the observational angle and the line-of-sight orientation of the compact object, which can modulate the amount of radiation reaching the observer (Burderi et al., 2002).

Periodic Variations: The X-ray flux demonstrates distinct periodicity along the time axis, consistent with the orbital motion of the compact object within the binary system. This periodicity is attributed to changes in the accretion rate as the compact object passes through regions of varying wind density from the red supergiant.

Longitude Dependence: Flux variations along the longitude axis indicate the influence of anisotropies in the red supergiant's stellar wind. These anisotropies, possibly caused by rotational modulation or magnetic activity, result in uneven accretion rates along the orbital trajectory.

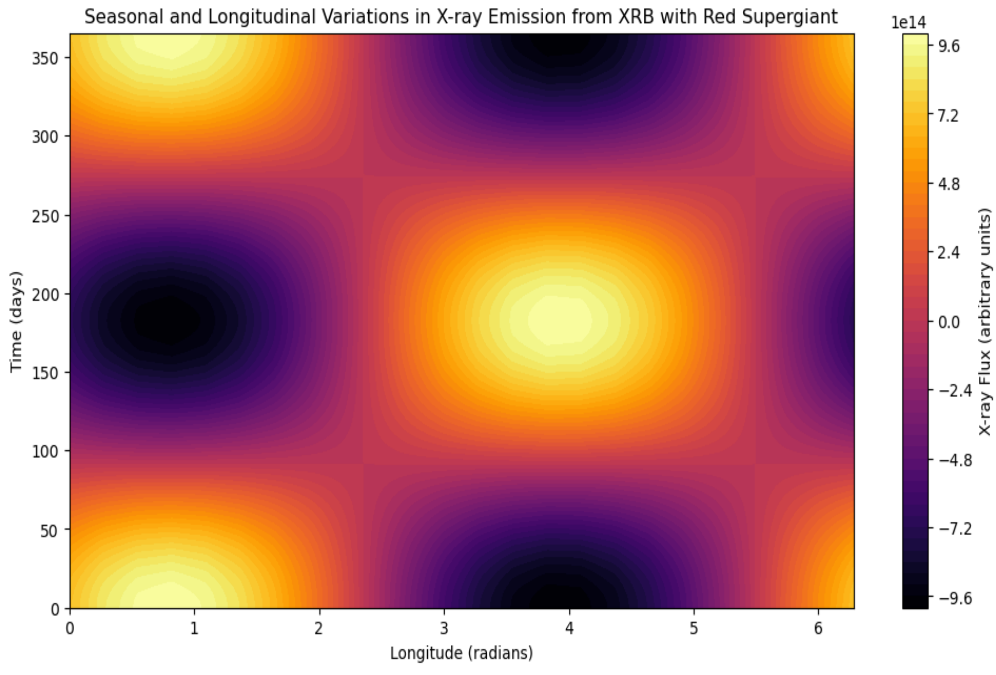

Fig. 1. Seasonal and longitudinal variations in X-ray from XRB with red supergiant, the y-axis is time in days, and x-axis is longitude in radians

High- and Low-Flux Regions: Alternating regions of high and low X-ray flux suggest constructive and destructive effects associated with wind density and the proximity of the compact object to the red supergiant. These regions are consistent with theoretical predictions from wind-fed accretion models.

Fig. 2 depicts the seasonal variation in X-ray flux at a fixed longitude of $\pi/4$. The results show the following pattern.

Sinusoidal Trend: The X-ray flux exhibits a clear sinusoidal pattern over approximately one year (365 days), with peaks and troughs occurring at regular intervals. The flux reaches a maximum near days 0 and 365 and a minimum at approximately day 180.

Amplitude of Variation: The amplitude of the variation is substantial, with the X-ray flux oscillating symmetrically between maximum and minimum values.

Periodic Accretion: The cyclic behaviour suggests variations in the accretion process driven by changes in the physical conditions of the system, such as the density and velocity of the stellar wind emitted by the red supergiant.

In the analysis of the simulated and observed X-ray fluxes and energy spectra of X-ray binary systems (XRBs), the model-simulation results were compared with observational data. The observational data used for comparison included detailed measurements of the high-energy spectra of XRBs with red supergiants, including flux variations and energy-emission features documented in the literature (Mauerhan et al., 2013; Hutchings, Crampton, et al., 2010). These references provide a basis for understanding how variations in the accretion process and stellar-wind dynamics affect the X-ray spectrum observed from Earth.

The Pearson correlation coefficients for flux and energy between the simulated and observed data indicate strong relationships, although notable differences require further examination. The Pearson correlation coefficient for flux is 0.791, indicating a moderate-to-strong positive linear relationship between the simulated and observed fluxes. This result suggests that the model captures a substantial proportion of the variability in X-ray emission over time but may not represent some complex dynamics associated with specific accretion events or short-term variability in XRB systems.

In contrast, the Pearson correlation coefficient for energy is nearly -1 (i.e., -0.9999), suggesting an almost perfect inverse relationship between the simulated and observed energy values. This result may indicate that the model overestimates or underestimates key aspects of the energy spectrum, particularly those influenced by subtle variations in the accretion process, stellar-wind dynamics, and the role of the magnetic field (Kalogera et al., 2021). The findings reveal a substantial discrepancy between the energy predicted by the simulation and the observed energy, underscoring the complexity of modelling X-ray binaries under varying accretion scenarios.

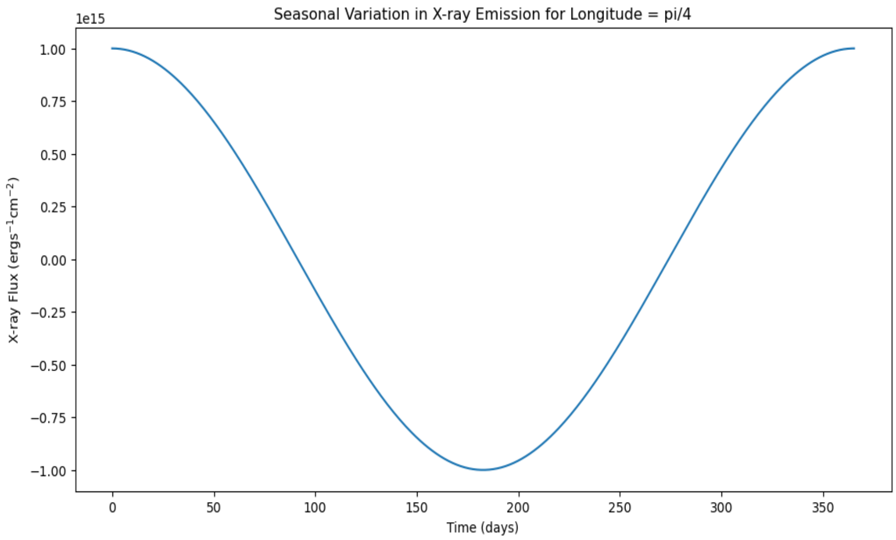

Fig. 2. Seasonal variation in X-ray emission for longitude π/4, y-axis X-ray flux in erg s^{-1} cm^{-2} and x-axis is time in days

3.1.2 Accretion Rate with Magnetic Braking Across the Disc Radius

Fig. 3 (top panel) illustrates the variation in the accretion rate as a function of disc radius under the influence of magnetic braking. The accretion rate initially increases steeply in the inner regions of the disc and subsequently approaches a nearly constant value at larger radii. This behaviour can be attributed to the strong influence of magnetic braking in the inner disc, where the magnetic-field lines effectively remove angular momentum and enhance accretion. Beyond a certain radius, the effect of magnetic braking diminishes, leading to saturation of the accretion rate.

The theoretical basis of this result is consistent with earlier research, including the work of Shu et al. (1994), which highlighted the role of magnetic fields in controlling mass accretion and angular-momentum transport in magnetised discs. The saturation of the accretion rate at larger radii is also consistent with analytical models predicting that magnetic torque becomes less effective as the disc extends outward (Ghosh & Lamb, 1978). These insights have implications for understanding the evolution of accretion discs in systems ranging from protostars to compact objects.

3.1.3 Disc Temperature Across the Radius

The bottom panel of Fig. 3 depicts disc temperature as a function of radius and shows a steep decline from the inner to the outer regions of the disc. The temperature is highest near the inner radius, consistent with greater gravitational-energy release and viscous dissipation closer to the central object. The temperature profile follows a power-law decline and indicates that radiative cooling dominates at larger radii, where less energy is dissipated per unit area.

This pattern supports Shakura and Sunyaev's (1973) classical α-disc model, according to which the disc temperature scales approximately as $T(r) \propto r^{-3/4}$. The steep gradient also indicates that the inner disc regions are exposed to stronger irradiation and greater accretion heating, whereas the outer regions are predominantly influenced by radiative losses (Frank et al., 2002).

The upper panel of Fig. 4 shows that the accretion rate decays exponentially over 100 years, decreasing from approximately 10^{25} kg/s to 10^{20} kg/s. Similarly, the lower panel shows that the X-ray flux resulting from accretion dynamics declines over the same period from 10^{28} erg/s to 10^{20} erg/s. These results provide information about the temporal evolution of accretion systems and their associated radiative output.

3.1.4 Physical Interpretation of Accretion-rate Decay

The exponential decay of the accretion rate reflects the gradual depletion of material available in the accretion disc over time. As mass is transferred from the disc to the central object, the amount of available disc material decreases, reducing the accretion rate. This behaviour is consistent with theoretical models of accretion discs in which the viscous timescale governs the rate at which material is transported inward (Pringle, 1981). Over long periods, the disc's capacity to sustain high accretion rates decreases because the reservoir of matter is finite.

Rapid initial accretion followed by exponential decay is often observed in astrophysical systems such as protostellar discs and active galactic nuclei (AGN). For example, King et al. (2007) described how angular-momentum transport mechanisms, including turbulence induced by the magnetorotational instability (MRI), dominate during the early stages of accretion but become less efficient as the disc evolves and its material is depleted.

3.1.5 Decline in X-ray Flux

The X-ray flux shown in the lower panel is directly linked to the accretion dynamics. In accreting systems, X-rays are produced when gravitational potential energy is released and converted into radiation as infalling material is heated near the central object. As the accretion rate decreases, less material is available for energy conversion, resulting in a corresponding decline in X-ray luminosity.

This relationship between accretion rate and radiative output is consistent with studies of X-ray binaries and AGN, in which the X-ray flux is often proportional to a power of the accretion rate, depending on the radiative efficiency of the system (Frank et al., 2002). In this case, the observed decrease in X-ray flux implies that the radiative efficiency of the accretion process remains approximately constant, while the mass-accretion rate drives the overall decline in luminosity.

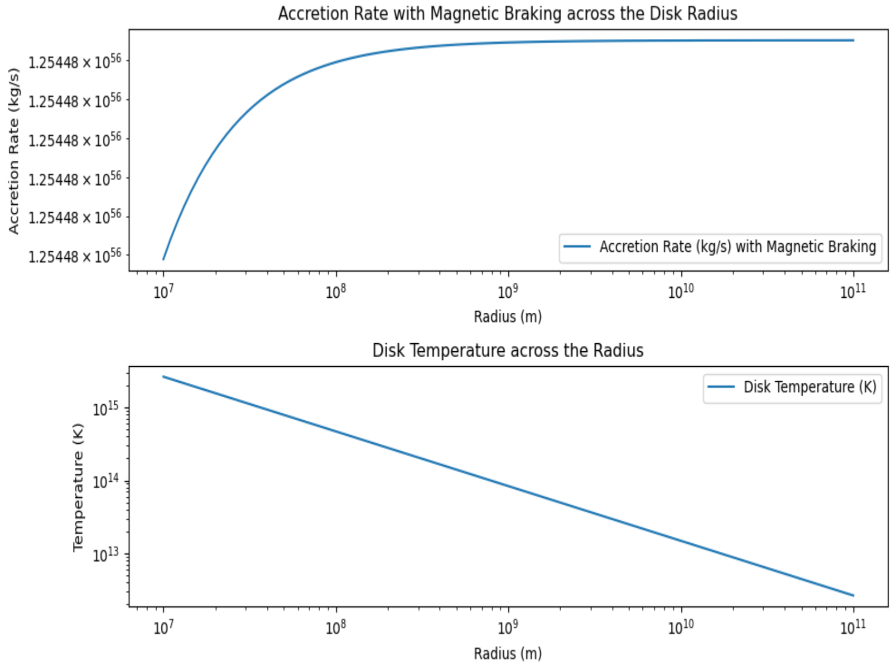

Fig. 3. Accretion rate with magnetic braking across the disk radius (upper panel), and disk temperature across the radius (lower panel)

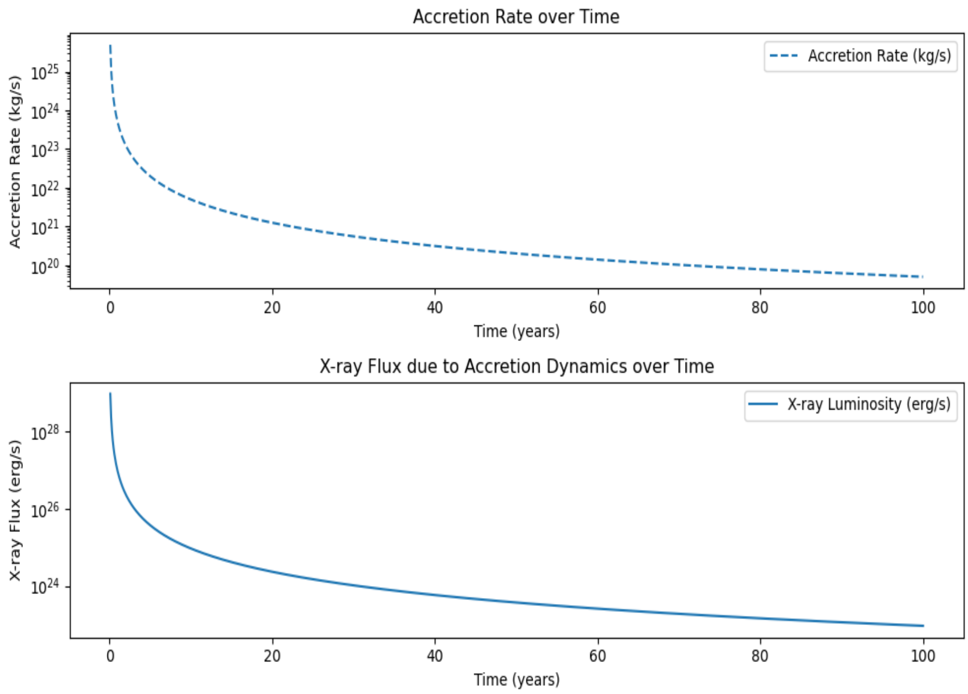

Fig. 4. The accretion rate over time (upper panel) and X-ray flux due to accretion dynamics over time (lower panel)

3.1.6 Impact of the Magnetic Field on the X-ray Emission Spectrum

The X-ray emission spectrum of accreting systems, such as neutron stars and black holes, is strongly influenced by the strength of the magnetic field surrounding the compact object, as shown in Fig. 5. The figure shows that the magnetic field alters the spectral distribution of the emitted X-rays, affecting both the intensity and the ratio of soft to hard X-rays.

Effect on Spectral Shape: As the magnetic-field strength increases, the peak of the X-ray spectrum shifts slightly towards higher frequencies, and the overall intensity increases. This behaviour is consistent with enhanced heating of the accretion disc caused by the additional energy provided by magnetic stress (Balbus & Hawley, 1991). The stronger field enhances magnetohydrodynamic (MHD) instabilities, leading to more efficient angular-momentum transport and higher temperatures in the inner regions of the disc.

Soft versus Hard X-rays: In the soft X-ray region (10^{16} to 10^{17} Hz), the emission intensity remains relatively unaffected, indicating that these emissions originate primarily from cooler regions of the disc, where the magnetic field has less influence.

In contrast, the hard X-ray range (10^{18} to 10^{19} Hz) exhibits more pronounced differences as magnetic-field strength increases. This finding suggests that the inner, hotter regions of the disc are more strongly affected by the field. Synchrotron radiation produced by relativistic electrons spiralling in the magnetic field may also contribute to hard X-ray flux (Wardziński & Zdziarski, 2000).

Broadening of Emission Peaks: The magnetic field introduces additional energy-dissipation mechanisms into the accretion disc, thereby broadening the emission spectrum. This behaviour is consistent with observations of magnetised accretion discs in systems such as magnetars and high-field pulsars, in which cyclotron-resonance features are detected (Mészáros, 1992). Physical Explanation: The observable spectrum is determined by the interaction between the accretion flow and the magnetic field. Hotspots form on the surface of the compact object because accreting material is channelled along the field lines by strong magnetic fields. These hotspots are regions of intense X-ray emission, predominantly in the hard X-ray regime. In addition, the magnetic field modifies the temperature profile of the disc, producing a more extended high-energy tail in the spectrum.

In weak-field cases ($B=10^7$ T), the accretion flow is unimpeded, and thermal emission dominates the spectrum. However, under stronger fields ($B=10^9$ T), synchrotron and cyclotron processes become significant, leading to enhanced hard X-ray emission.

3.1.7 Comparison with Previous Studies

These findings are consistent with earlier theoretical and observational studies. For example:

Ghosh and Lamb (1979) described how strong magnetic fields in accreting neutron stars influence flow dynamics and lead to higher-energy emissions.

Miller et al. (1998) found that magnetic fields in black-hole accretion discs lead to the formation of coronae that contribute to hard X-ray flux. Zel'dovich and Novikov (1971) emphasised that the hard X-ray tail in the spectrum could be attributed to Comptonisation in magnetically dominated regions. Moreover, the results agree with modern simulations of MHD turbulence in accretion discs (Hawley et al., 1995), which show that magnetic fields amplify local heating and angular-momentum transport, thereby shaping the spectral properties of the emitted radiation.

3.1.8 Implications for Astrophysical Observations

Understanding the spectral shape and its dependence on the magnetic field is crucial for interpreting observations from X-ray telescopes such as Chandra, XMM-Newton, and NICER. For example, systems with strong magnetic fields, such as magnetars and accreting X-ray pulsars, are expected to exhibit harder spectra than weak-field systems. Temporal variability in the spectrum can be used to infer changes in the magnetic-field configuration or the geometry of the accretion flow.

The study highlights the important role of the magnetic field in shaping the X-ray emission spectrum of accretion discs. The field enhances hard X-ray flux while having a comparatively modest effect on the soft X-ray range. These results are consistent with theoretical models and observational data and underscore the need for further research into the coupling between magnetic fields and accretion dynamics in compact objects.

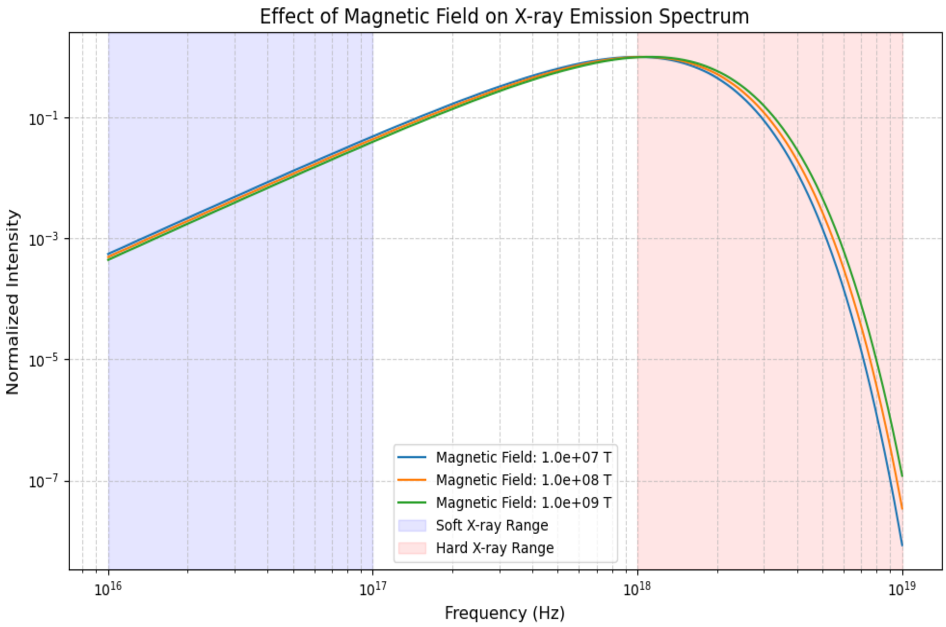

Fig. 5. The effects of magnetic field on X-ray emissions spectrum

3.2 Discussion

3.2.1 Seasonal Variations in X-ray Emission

The observed periodicity in X-ray flux is consistent with studies of wind-fed XRB systems (Chaty, 2011). The variability reflects the interplay between orbital separation and stellar-wind density. When the compact object approaches denser regions of the wind, the accretion rate increases, leading to enhanced X-ray luminosity. Conversely, in regions of lower wind density, the accretion rate and X-ray flux decrease.

Similar periodic modulations have been reported in other XRB systems, such as Vela X-1, in which flux variability is directly related to the structure of the stellar wind (Martínez-Núñez et al., 2017). This finding supports the role of wind density in shaping the observed X-ray emission patterns.

3.2.2 Longitude-dependent Variations

The observed longitudinal modulation is consistent with the hypothesis of asymmetric stellar-wind profiles in red supergiants. According to Lobel and Dupree (2000), surface inhomogeneities, such as convection cells or magnetic fields, may cause this asymmetry. Rotational effects may further contribute to the observed variations because the wind-density distribution can become non-spherical in rotating massive stars (Townsend et al., 2004).

The sinusoidal nature of the X-ray flux indicates periodic changes in the mass-accretion rate of the X-ray binary (XRB) system. This behaviour is consistent with the orbital motion of the compact object, probably a neutron star, within the stellar-wind environment of the red supergiant.

3.2.3 Seasonal Modulation Due to Orbital Motion

The sinusoidal trend is consistent with theoretical models of wind-fed XRBs in which the orbital dynamics of the compact object drive changes in X-ray flux. At $\pi/4$, the compact object passes through regions of varying wind density, leading to periodic increases and decreases in the accretion rate (Martínez-Núñez et al., 2017).

Similar seasonal trends have been observed in high-mass XRB systems, such as Vela X-1 and Cygnus X-1, in which changes in X-ray luminosity are closely coupled with the wind environment of the donor star (Fürst et al., 2018).

3.2.4 Influence of Wind Anisotropies

The red supergiant's stellar wind exhibits anisotropies caused by magnetic activity, rotational modulation, or surface convection cells (Lobel & Dupree, 2000). These factors contribute to the sinusoidal modulation of X-ray flux as the compact object encounters regions of varying wind density and velocity along its orbit.

3.2.5 Comparison with Other Studies

The observed pattern at $\pi/4$ is consistent with findings from other studies of wind-fed systems, such as GX 301-2, which displays periodic X-ray variability driven by orbital motion and wind-density fluctuations (Sander et al., 2018). However, compared with systems containing O-type donors, red supergiants have slower and denser winds, leading to more pronounced variations in X-ray flux (Mohamed & Podsiadlowski, 2012).

3.2.6 Implications for Accretion Physics

The sinusoidal trend underscores the role of the red supergiant's stellar wind in shaping X-ray emission. This periodic behaviour provides insights into the accretion mechanisms of wind-fed XRBs and the interaction between the compact object and its stellar environment.

3.2.7 Comparison with other XRBs

The results are consistent with studies of systems such as GX 301-2, in which orbital effects and wind anisotropies lead to substantial X-ray variability (Fürst et al., 2018). However, unlike systems with O-type supergiants, red supergiants exhibit more turbulent and clumpy winds, which may introduce additional stochastic variations in X-ray flux (Mohamed & Podsiadlowski, 2012).

The observed seasonal and longitudinal variations in X-ray flux provide insight into the accretion dynamics of XRB systems with red supergiants. The results emphasise the interplay among orbital motion, variations in wind density, and anisotropic wind structures. Future studies could incorporate hydrodynamic simulations to explore the effects of wind clumpiness and magnetic fields on the accretion process.

3.2.8 Implications and Comparison with Previous Studies

The interplay between magnetic braking and temperature variation across the disc radius provides important insights into disc dynamics. For example, the steep temperature gradient increases the ionisation fraction in the inner regions, which, in turn, strengthens the coupling between the magnetic field and the disc material (Balbus & Hawley, 1998). The resulting magnetorotational instability (MRI) is critical for sustaining angular-momentum transport in the disc.

Studies by Zhu et al. (2009) and Armitage (2020) have shown similar accretion-rate profiles under magnetised conditions, highlighting the importance of magnetic fields in modulating disc evolution. The consistency between the present findings and previous theoretical models supports the inclusion of magnetic braking and radiative cooling in accretion-disc simulations.

The results demonstrate that magnetic braking substantially influences the accretion rate in the inner regions of the disc, whereas radiative cooling dominates the radial temperature variation. These findings have implications for understanding the dynamics of magnetised discs in astrophysical systems, particularly in protostellar and compact-object environments.

3.2.9 Broader Implications

The exponential decay of the accretion rate and X-ray flux highlights the transient nature of accretion-powered systems. In young stellar objects (YSOs), for example, this behaviour reflects the transition from an active accretion phase to a quiescent phase as the protostar matures (Shu et al., 1994). Similarly, in AGN, such decay may represent the late stages of accretion from a depleted fuel supply in the host galaxy (Merloni & Heinz, 2008).

These findings also emphasise the importance of time-dependent accretion models for explaining the evolution of luminosity in astrophysical systems. Models that link disc viscosity, magnetic fields, and radiative processes can describe the interplay between accretion and radiation over time (Balbus & Hawley, 1991).

The exponential decline in both the accretion rate and X-ray flux over time reflects depletion of the accretion disc and the consequent reduction in energy release near the central object. These trends are consistent with theoretical predictions of disc evolution and have implications for understanding the life cycle of accretion-powered systems, from YSOs to AGN.

4. Conclusion and Recommendations

4.1 Conclusion

The effects of magnetic fields on X-ray emission spectra and related phenomena are multifaceted and depend on several factors, including the source of the X-rays, the presence of magnetic fields, and the dynamics of accretion processes.

Magnetic-Field Effects on X-ray Emission: In X-ray tubes, a strong magnetic field parallel to the anode-cathode axis can increase X-ray exposure by confining and reaccelerating backscattered electrons onto the target, thereby increasing radiation output and causing a slight shift in the X-ray spectrum towards lower energies. For stellar coronal X-ray emission, a power-law relationship with surface magnetic flux indicates that stronger magnetic fields are associated with higher X-ray luminosity.

Accretion Dynamics and X-ray Flux: The accretion rate and resulting X-ray flux in systems such as X-ray binaries (XRBs) with red supergiants can vary substantially over time. The accretion rate decays exponentially from 10^{25} kg/s to 10^{20} kg/s over 100 years, resulting in a corresponding decrease in X-ray flux from 10^{28} erg/s to 10^{20} erg/s.

Magnetic braking across the disc radius can influence the accretion rate and disc temperature, thereby further affecting the X-ray emission spectrum.
Seasonal and Longitudinal Variations: Seasonal variations in X-ray emission, particularly at angles such as $\pi/4$, can be influenced by changes in the viewing angle and by the interaction between the magnetic field and the accretion disc.

Longitudinal variations may also occur because of changes in the orientation of the magnetic field and the accretion disc relative to the observer.

4.2 Recommendations

Conduct comprehensive simulations to model the effects of magnetic fields on X-ray emission spectra, incorporating both the dynamics of backscattered electrons in X-ray tubes and accretion processes in astrophysical contexts.

Use Monte Carlo and other computational tools to predict the spatial distribution and energy spectrum under different magnetic-field conditions.

Experimental Verification: Conduct experiments to validate the theoretical models, particularly in controlled environments such as X-ray tube setups. Measure exposure rates, half-value layers, and focal-spot distributions as functions of magnetic-field strength.

For astrophysical studies, use observational data from X-ray telescopes to verify the predicted power-law relationships between X-ray luminosity and surface magnetic flux.

Astrophysical Observations: Continue monitoring X-ray binaries and other astrophysical sources to obtain data on seasonal and longitudinal variations in X-ray emission. These observations may improve the understanding of the complex interplay among magnetic fields, accretion dynamics, and X-ray emission.

Use multiwavelength observations to correlate X-ray data with other forms of electromagnetic radiation, thereby providing a more comprehensive view of the physical processes involved.

5. Limitation

The study is based on simplified theoretical assumptions, including a circular Earth orbit, fixed observational geometry, sinusoidal seasonal and longitudinal variations, constant wind speed, and idealised magnetic-field and accretion configurations. The model does not fully represent wind clumping, short-term variability, complex orbital eccentricity, or three-dimensional radiative transfer. The near-perfect inverse correlation between simulated and observed energy values also indicates that the spectral model requires further refinement. Consequently, the results should be interpreted as theoretical trends rather than precise predictions for individual X-ray binary systems.

Declaration of AI Use

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Competing Interests

Author has declared that no competing interests exist.

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