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Theoretical Perspectives on Accretion Processes in Weakly Magnetized Neutron Star Systems

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Abstract:
Transferring matter from a companion star onto the surface of a neutron star through an accretion disc is a basic process in high-energy astrophysics known as accretion onto weakly magnetised neutron stars. Since the disc can get rather close to the star due to its weak magnetic field, the activities occurring in the boundary layer and the dynamics of the disc are essential to comprehending the processes of energy release and X-ray emission. In this survey, we look at the theories that underpin accretion, such as radiation processes, disc structure, angular momentum transit, and viscous processes. Additionally, it covers observational events like X-ray bursts and quasi-periodic oscillations, as well as current theoretical models and magnetohydrodynamic effects. The study adds to our knowledge of neutron star systems and compact object astrophysics by highlighting current achievements and future difficulties in simulating accretion fluxes in the presence of extremely harsh physical circumstances.

Keywords: Weakly Magnetized Neutron Stars, Accretion Disks, Accretion Processes, X-ray Binaries.

I.INTRODUCTION

Among the most crucial topics in contemporary high-energy astrophysics is the study of accretion processes in neutron star systems with weak magnetic fields. With extraordinarily high densities, powerful gravitational fields, and fast rotational velocities, neutron stars are compact relics of enormous stars that have experienced supernova explosions. A neutron star will frequently accrete mass from its partner star in binary star systems. These systems are among the most intense X-ray emitters because the gravitational potential energy generated when matter falls is transformed into thermal and radiative radiation. The interpretation of various observational phenomena, such as X-ray bursts, quasi-periodic oscillations, spectral state transitions, and high-energy emissions in low-mass X-ray binaries, relies on a solid theoretical grasp of accretion onto weakly magnetised neutron stars.

The accretion flow's geometry and dynamics are strongly affected by the neutron star's magnetic field intensity. The inner accretion disc is disrupted and matter is channelled towards the magnetic poles in neutron stars with a strong magnetic field. Nevertheless, the accretion disc can reach somewhat closer to the stellar surface in neutron stars with weak magnetisation, whose magnetic field strengths are usually less than 10^9-10¶^{0} gauss. Consequently, the systems reported features are mostly shaped by the interaction between the neutron star surface and the inner accretion disc. Weakly magnetised neutron stars are perfect test beds for studying the basic physics of disc accretion, angular momentum transport, and energy dissipation in extremely dense environments because of this property.

Neutron star systems are unique among accreting objects due to the extra complexity introduced by the neutron star's strong gravitational field. As one moves deeper into the accretion disc, the influence of general relativity on particle trajectories, disc structure, and radiation emission becomes more significant. The presence of gravitational redshift, frame dragging, and innermost stable circular orbits are all phenomena that theoretical models frequently include relativistic corrections for. The matter dynamics close to the neutron star is affected by these factors, which in turn cause the high-frequency variability seen in X-ray measurements. Therefore, contemporary accretion theories cannot function without relativistic physics.

How radiation fields interact with accretion flows is another key theoretical viewpoint. Massive X-ray and other high-energy radiation bursts forth from neutron stars when stuff piles up on their surfaces. A change in the structure and stability of the accretion flow can occur when the emitted radiation presses on the inflowing matter. Significant changes in disc geometry and energy transport mechanisms may occur in systems with high accretion rates when radiation pressure becomes equal to or greater than gas pressure. To study these processes and to account for the spectrum states observed in neutron star systems that are accreting, radiation hydrodynamic models have been built.

Research into neutron stars with weak magnetic fields has also profited substantially from developments in computational astrophysics. In order to understand how accretion flows behave under realistic settings, current numerical models include hydrodynamics, magnetohydrodynamics, and radiation transport. Research into phenomena including turbulence, disc instabilities, shock production, and boundary layer dynamics—which include several dimensions—can now be explored through these simulations, which were previously only possible with analytical models. The theoretical predictions of neutron star accretion systems have grown more complex and accurate in recent years, thanks to the exponential growth in computing power.

Over the past few decades, a plethora of fluctuation events linked to neutron stars that are accreting have been uncovered by X-ray studies taken by satellite facilities. Some examples of these phenomena include thermonuclear X-ray bursts, spectral state transitions, and kilohertz quasi-periodic oscillations. These phenomena are useful for testing theoretical theories. A complete knowledge of the interaction between radiation processes, neutron star surface physics, and accretion dynamics is necessary for theorising these events. So, bridging theoretical astrophysics, observational astronomy, plasma physics, and general relativity, the study of accretion processes in weakly magnetised neutron star systems is a growing and dynamic area.

II.REVIEW OF PREVIOUS STUDIES

Shakura, Nikolay et al., (2018). Theoretical framework for quasi-spherical subsonic accretion onto magnetised neutron stars in a slowly rotating state is laid out. In this phase, an extended quasi-spherical shell is formed as the accreted matter settles onto the rotating magnetosphere at subsonic velocities. The pace of shell accretion is defined by the plasma's Rayleigh-Taylor instability with cooling, which allows it to enter the magnetosphere. The presence of a free-fall gap at greater accretion rates is caused by the intense Compton cooling of the flow above the magnetosphere, rendering accretion extremely non-stationary. Determination of the basic dimensionless model parameters and estimation of the neutron star magnetic field are made possible by observations of spin-up and spin-down in equilibrium wind-fed X-ray pulsars with known orbital periods, such as GX 301-2 and Vela X-1. The model permits the independent estimation of the stellar wind velocity in equilibrium pulsars with magnetic fields that have been observed separately. There is an upper limit to the spin-down rate of the neutron star accreting to a non-equilibrium pulsar. If the stellar winds of the O-supergiant partners are magnetised, the model can also account for brilliant flares in Supergiant Fast X-ray Transients.

Mallick, Ritam & Schramm, Stefan. (2014). Compact stars known as magnetars have extremely powerful surface magnetic fields, measuring 1014-1015 G, according to observations. A magnetic field that is many orders of magnitude stronger could exist in the star's core. We investigate how the field influences the size and form of such a star. We generally take the density-dependent nonuniform internal magnetic field of the star for granted. Multipole expansions in spherical harmonics are applied to the metric, magnetic energy and pressure, and all the way up to the quadrupole term. As a function of the magnetic field, the correction terms can be obtained by solving the Einstein equations for the gravitational potential. Under a nonlinear model of the hadronic EoS, with a surface field of 1015 G and a central field of roughly 1018 G, the star's extra mass and the change in its equatorial radius caused by the magnetic field are rather substantial. As opposed to the spherical solution, we see a 3-4% decrease in the star's excess mass and equatorial radius at a central magnetic field intensity of 1.75×1018 G.

Chashkina, Anna & Popov, Sergei. (2011). Neutron star models that are more up-to-date suggest that lesser magnetic fields do not undergo considerable decay (Pons), but larger magnetic fields quickly decrease to a saturation value of around few × 0 13 G. On a time scale of a few million years, it is challenging to verify the predictions of this model for initially highly magnetised objects. We suggest that Be/X-ray binaries be utilised for this objective. Using data from the RXTE satellite (Galache), we estimate the magnetic fields of neutron stars in these accreting systems using a number of methods. An up-to-date method for calculating the magnetic field strengths of long-period NSs, as put out by Shakura, is the sole way to get a field distribution that agrees with Pons's predicted theoretical field decay.

Potekhin, Alexander. (2011). We go over the fundamentals of neutron stars as well as some current issues in their physics. The microphysics behind neutron stars is quickly covered, along with their observed properties, such as their magnetic fields, thermal evolution, masses, radii, core and envelope structures, and observational manifestations.

III.WEAKLY MAGNETIZED NEUTRON STARS AND THEIR PHYSICAL CHARACTERSTICS

When compared to traditional X-ray pulsars, the magnetic field strengths of compact stellar remnants known as weakly magnetised neutron stars are far smaller. The surface magnetic fields of these objects usually aren't strong enough to significantly disturb the inner parts of the accretion disc, and they range from about 10^7 to 10^{10} gauss. Thus, accreting material can flow inward almost to the surface of the neutron star before magnetic effects become noticeable. When a neutron star absorbs material from another star, either through stellar winds or Roche lobe overflow, these systems are often seen in low-mass X-ray binaries. They are perfect astrophysical labs for researching the severe gravitational interaction between compact star surfaces and accretion discs since their magnetic fields are relatively faint.

The extraordinarily high density of weakly magnetised neutron stars is one of the most striking physical features of these objects. The mass of a typical neutron star is 1.2–2.3 times that of the Sun, all packed into a spherical object with a radius of just approximately 10-15 kilometres. The typical densities surpass 10^{14} g cm^{-3} due to the extremely high mass concentration, which is similar to the density of atomic nuclei. Matter exists in unusual states that terrestrial laboratories cannot replicate under these conditions. Superfluid neutrons, hyperons, superconducting protons, and deconfined quark matter could be found in the interiors of neutron stars, according to theoretical models. Thus, indirect insights into matter behaviour at supranuclear densities can be obtained from the study of accretion onto weakly magnetised neutron stars.

Because neutron stars are so dense and massive, the gravitational field acting on their surface is extremely powerful. Gravitational accelerations on Earth's surface are usually about ten times stronger than the force of gravity on the surface itself. By pushing infalling matter to speeds approaching a substantial fraction of the speed of light, this powerful gravitational field is an essential component of the accretion process. Among the most intense X-ray sources in the cosmos, neutron stars are among the most active when matter falls on their surfaces, converting a large amount of gravitational potential energy into heat and radiation. The spectra and time features of these systems are affected by relativistic phenomena, such as gravitational redshift and light bending, which are caused by heavy gravity.

Fast rotation speeds greatly impact the structure and observable properties of neutron stars with weak magnetisation. Spin durations in the millisecond range are produced by several of these objects as a result of their hundreds of rotations per second. The consensus holds that spin-up, a process where the neutron star gains angular momentum from the accretion disc, is the likely cause of such fast spinning. Once the accretion period is over, these neutron stars can often be seen as millisecond pulsars due to their rapid rotation. When weak magnetic fields are combined with fast rotation, it affects the dynamics of accretion flows, the creation of boundary layers, and the generation of high-frequency oscillations shown by X-ray emissions.

Weakly magnetised neutron stars have quite different magnetic fields than strongly magnetised ones. The accretion geometry is dominated by magnetic fields in conventional X-ray pulsars, which can reach strengths of 10´^{2}-10¶^{3} gauss. However, in low-mass X-ray binaries, where the magnetic fields are smaller, the accretion disc can extend nearly to the star surface. Therefore, magnetic channelling is not the main governing factor in the inner disc dynamics, but rather gravitational, hydrodynamic, and relativistic effects. Certain parts of the accretion theory are simplified by the lessened influence of magnetic fields, while the significance of disc viscosity, turbulence, and boundary layer physics is highlighted at the same time.

The existence of a solid surface is another crucial physical characteristic of weakly magnetised neutron stars. Neutron stars, in contrast to black holes, which have an event horizon, offer a physical barrier along which matter can be accreted and energy can be released. The accretion disc material must slow down from almost Keplerian orbital velocities to the neutron star's rotational velocities when it approaches the stellar surface. A boundary layer, a region of high energy dissipation, is where this change happens. The resultant radiation is a rich source of information about the physical conditions close to the star surface and adds a lot to the observed X-ray brightness.

Weakly magnetised neutron stars are distinct from other compact astronomical objects due to their physical properties. They are able to host a plethora of basic physical processes due to their solid surfaces, high density, strong gravity, fast rotation, and weak magnetic fields. Not only do these features define accretion flows and high-energy emissions, but they also provide great chances to study how matter and radiation behave in environments that are impossible to replicate on Earth. As a result, neutron stars with weak magnetisation are nonetheless important for both theoretical and observational astrophysical investigations, since they shed light on compact objects, accretion physics, and the universal laws.

IV.RADIATIVE PROCESSES AND ENERGY TRANSFER MECHANISM

The observational features of neutron star systems with weak magnetic fields are strongly influenced by radiative processes and energy transfer mechanisms. The neutron star transforms a vast quantity of gravitational potential energy into heat, motion, and finally electromagnetic radiation as it absorbs matter from a companion star through its accretion disc. In neutron star environments, the energy released per unit mass of accreted material is far more than in normal stellar environments because neutron stars have extraordinarily strong gravitational fields. Because much of this energy is released as X-rays, accreting neutron stars are some of the most intense cosmic light sources. In order to construct complete theoretical models of neutron star accretion, it is crucial to comprehend the processes of energy generation, transport, and radiation.

As matter spirals inward via the accretion disc, gravitational potential energy is converted into heat, which is the main source of energy in neutron star systems that are undergoing accretion. Matter in the disc loses its angular momentum and moves towards the neutron star as a result of viscous interactions throughout this process. The material is accelerated to even higher velocities by gravitational forces as it gets closer to the compact object. The disc becomes very hot as a result of the ensuing friction and turbulence, which in turn causes it to radiate radiation at many different wavelengths. Optical and ultraviolet radiation is emitted mostly by the cooler core disc areas, whereas soft X-rays are emitted mainly by the outer portions. The accretion disk's temperature structure and geometry determine the radiation dispersion across different wavelengths.

Multiple processes, such as radiation, convection, and conduction, contribute to the radiative energy transfer inside the accretion disc. Radiative diffusion is the main process that moves energy out of the dense interior of an accretion disc and onto its surface in the majority of discs that include weakly magnetised neutron stars. Viscous heating causes photons to interact with matter around them several times before they finally escape into space. The density, opacity, temperature, and disc material composition determine the process efficiency. To find out how energy is dispersed in the accretion flow, theoretical models of disc structure often solve coupled equations describing hydrodynamics and radiative transfer.

In the context of neutron star accretion, Compton scattering is an additional important radiative mechanism. This process works by having low-energy photons interact with hot electrons in the accretion flow or the corona to increase their energy. Inverse Compton scattering is a mechanism that can generate higher-energy X-rays and gamma rays, which can drastically change the radiated spectrum. The strong X-ray emission seen in many neutron star systems is typically explained by the existence of a hot, optically thin corona above the accretion disc. Theoretical models that include Comptonization are able to replicate numerous spectrum patterns found by contemporary X-ray observatories.

The neutron star's ionised plasma is heated and losing energy due in part to bremsstrahlung radiation, which is another name for free-free emission. The acceleration of charged particles, especially electrons, in the electric fields of ions results in the production of this radiation. When particle collisions are common in optically thin portions of the accretion flow, bremsstrahlung takes on a greater significance. Bremsstrahlung is a significant part of the total energy budget and helps explain the high-energy spectral continuum in some systems, even though it is typically less prominent than thermal disc emission and Compton scattering.

Energy transfer and accretion dynamics are strongly influenced by radiation pressure, especially at high accretion rates. The radiation field can counterbalance the gravitational attraction as the system's

luminosity gets close to the Eddington limit. In such a scenario, radiation pressure has the potential to change the accretion disc structure, alter the rates of mass influx, and generate strong outflows or winds. An important area of theoretical enquiry is the knowledge of the distinctions between radiation-dominated discs and gas-pressure-dominated discs, as the two types of discs display different physical features. In order to understand these intricate interactions, radiation hydrodynamic models are now indispensable.
The neutron star itself is a site of energy transfer. Accumulated material presses on lower crustal layers, releasing heat via nuclear processes, as it builds up on the surface. The thermal evolution of the neutron star is affected by the inward and outward transmission of this heat via conduction and radiation. Thermonuclear runaway reactions can occur when hydrogen and helium are collected to a certain point, and the result is Type I X-ray bursts that quickly release tremendous amounts of energy. An in-depth familiarity of nuclear power, heat transfer, and radiative cooling mechanisms is necessary for the development of theoretical models of these explosions.

V.CONCLUSION

Since it offers a one-of-a-kind setting to study strong gravity, high-density matter, plasma dynamics, and intense radiation fields, the study of accretion into weakly magnetised neutron stars is an important subfield of high-energy astrophysics. Weakly magnetised neutron stars are perfect for researching disc accretion, boundary layer formation, and energy dissipation because the accretion disc can reach close to the stellar surface, unlike strongly magnetised neutron stars. The formation and evolution of accretion discs, which are driven by angular momentum transport and magnetorotational instability (MRI), have been satisfactorily described by theoretical models. The observed X-ray emission is mainly caused by the conversion of kinetic energy into radiation that occurs in the boundary layer that forms when a solid neutron star surface is present. Radiative processes such nuclear burning, thermal emission, Compton scattering, and bremsstrahlung are critical in generating the high-energy radiation seen in these systems. Our knowledge of disc turbulence, instabilities, and boundary layer dynamics has been substantially enhanced by developments in computational astrophysics, such as magnetohydrodynamic, radiation hydrodynamic, and relativistic simulations. There are still major obstacles to overcome, such as deciphering angular momentum transmission, boundary layer structure, weak magnetic field effects, and the ultra-dense matter equation of state, along with other crucial issues. Experiments using X-ray bursts, spectral state transitions and quasi-periodic oscillations are ongoing efforts to improve and validate theoretical frameworks. The overall picture is that accretion onto weakly magnetised neutron stars is a great way to learn about strong-field gravity, nuclear astrophysics, compact objects, and plasma physics.

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