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Remarking

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A Review on Accretion Physics of X-ray Pulsars

Abstract

In this review paper I will discuss the physics of accretion of X-ray pulsars. X-ray pulsars are neutron stars. Radiation from these neutron stars comes on earth in the form of pulses of X-ray radiation hence these neutron stars are called X-ray pulsars. Neutron stars are compact stellar objects. These objects are strange in many sense. They posses very high magnetic fields 10^8 to 10^{15}gauss). Earth's magnetic field is of the order of 1 gauss. In case of sun the maximum magnetic field occurs at sunspots (3000 gauss). Neutron stars also posses very high gravitational field 2 x 10^{11}g while the surface gravity of sun is 28 g. One can see that neutron stars are indeed very exotic objects. Neutron stars are the natural laboratories to test the fundamental laws of physics.

Some of the neutron stars are found in isolation and some others are found in binary systems. Neutron stars accreting plasma from companion star. This flow of plasma is disrupted where magnetic field becomes strong enough to disrupt the flow of the plasma. Plasma then follows the magnetic field lines and falls on the magnetic poles of the neutron star surface. When plasma reaches near the neutron star surface it is decelerated either by radiative shock formation or by Coulombic shock formation. Plasma settles down inside the tube like geometry on polar cap region called accretion column. A heap of plasma is created at the base of the accretion column which is called plasma mound. The height of the accretion column depends upon the X-ray luminosity of the source.Finally I have summarized accretion physics of X-ray pulsars in the end.

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Introduction

The theoretical concept of neutron stars was proposed by L. D. Landau in the 1930s. The first signal of a neutron star was observed by Hewish et al. in 1968. Since then neutron stars have emerged as very fascinating celestial objects. Very high magnetic fields and strong gravity of the neutron stars provide a unique laboratory to test fundamental laws of physics. All sub-classes of neutron stars (isolated neutron stars and neutron stars in binary system) have very high surface magnetic fields between 10^8 to 10^{15} G.

Neutron stars in binary systems which accrete material from a binary companion and show periodic modulation of X-ray flux are called accreting X-ray pulsars (White, Swank & Holt 1983, Nagase 1989, Bildsten et al.1997) In these sources the gravitational energy of the accreted material is released in the form of X-ray radiation. X-ray binaries can be classified as low mass X-ray binaries (LMXBs) and high mass X-ray binaries (HMXBs) depending upon the mass of the companion. In this review paper I will discuss the accretion physics of neutron stars which are found in binary systems.

Aim of the Study

The aim of this paper is to study the accretion phenomenon in X-ray pulsars.

This paper explains accretion phenomenon in following steps

1. The plasma is captured by neutron star
2. The ow of plasma is disrupted by strong magnetic eld of neutron star
3. Plasma falls on magetic poles of neutron star and forms accretion column
4. Height of the accretion column depens on neutron star luminosity.

Accretion on to a Neutron Star

Accretion Capture Radius

The plasma is transferred from a companion star to a neutron star via Roche lobe overflow or through capture of stellar wind. The gravity of neutron star starts affecting the flow of matter at the accretion capture radius R_G (where R_G is measured from center of the neutron star). An order of magnitude estimate of R_G in sources,where accretion occur through capture of accretion wind, can be made while equating the kinetic energy of the matter equals to the gravitational energy.

$$R_G = 2GM_*/v^2_{rel}$$

Where u_{rel} is the velocity of flow relative to the neutron star. For typical value of neutron star mass $M_*=1.4M_\odot$ and the velocity of the flow u_{rel} =1000 km s^{-1}, the value of accretion capture radius R_G comes out of the order of 10^5 km.

Here $M_\odot$ stand for solar mass in grams (i.e $M_\odot$ =1.98 x10^{33}grams).

Alfven Radius

The matter captured at R_G falls towards the neutron star up to the Alfven radius R_A where the magnetic field of the neutron star stops the flow of in-falling material. At the Alfven radius the kinetic energy density of the accreting material becomes comparable to the energy density in magnetic field

$$(P_{mag}(R_A) = pu^2=R_A)$$

The dependence of R_A on the luminosity and the parameters of the neutron star may be expressed as (Frank, King and Raine (2002))

$$R_A \approx 2.9X10^8 m_1^{-2/7} R_6^{-2/7} L_{37}^{-2/7} \mu_{30}^{4/7} cm$$

where neutron star parameters are defined as, m_1=M/ $M_\odot$,R_6=R/(10^6cm), L_{37} = L/10^{37}erg s^{-1}), μ_{30} = μ/ (10^{30}Gauss cm^2) and R, L, μ are measured in cm, erg s^{-1}, gauss cm^{-1} respectively. For $m_1 \approx R_6 \approx L_{37} \approx \mu_{30}$ value of $R_A \approx 2.9X10^8$ cm

Mode of Accretion R_G to R_A

The flow of matter from R_G to R_A, depending upon the strength of the gravitational force and the angular momentum, occurs in three basic accretion types

1. Quasi spherical accretion
2. Disk accretion
3. Two stream accretion (occurrence of both the spherical accretion and the disk accretion).

The plasma interacts with the magnetosphere at the Alfven radius R_A, proceeds freely along the magnetic field lines connecting the stellar surface with R_A, and falls in the polar cap region. Most of the X-ray radiation is produced when the plasma is decelerated by radiative shocks or Coulombic collisions near the neutron star surface.

Formation Accretion Column and Accretion Mound on Polar Cap

X-ray radiation is produced on polar cap in a tube like structure (accretion column or polar column) by deceleration of the matter flow due to the radiative or gas shocks (collisionless or collisional).

The plasma settles down in post shock region with relatively very small velocities and forms a optically thick heap of plasma called accretion mound. Building a self consistent physical model for the polar cap accretion is a difficult task due to the extreme physical conditions prevailing near the neutron star's surface: relativistic flow of plasma v~c/2, strong magnetic fields B~10^{12}G, and sometimes due to presence of super Eddington luminosities.

Geometry of Accretion Column

In reality geometry of the accretion column (X-ray production zone) and accretion mound may be very complex and there are several reasons for it. The column shape may be asymmetric and column may not be fully filled. The heavy mass loading in field lines at the base of the mound may trigger magnetohydrodynamical instabilities and material at the base of the mound may spread over the neutron star surface in a very complicated way.

The column actually may be of funnel shape but is approximated as cylindrical or slab shaped in the literature (Nagel (1980, 1981), Isenberg et al. (1998a,b), Araya and Harding (1999)).

Radius of Accretion Column R_{pole}

The radius R_{pole} of the circular base of the column (also called polar cap radius) may be estimated to an order of magnitude by assuming the magnetic field to be dipolar. The equation of the dipolar magnetic field is

$$R=R_e \sin^2(\theta) \qquad 2.3$$

where R_e is the radial distance of the field line at the magnetic equator and R is the radial co-ordinate of the point at the same field line at angle θ (which is measured from magnetic axis). The half angle θ_{pole} which the circular base of accretion column makes at the center of neutron star can be estimated by assuming that the flow of matter from companion star is disrupted at the magnetic equator at the Alfven radius R_A. The dipolar magnetic field line which passes at R_A at magnetic equator touches the periphery of circular base at the neutron star surface. In this case R_e= R_A and at $\theta=\theta_{pole}$ the value of R equals to R_*.

So putting these values in equation of dipole eld equation,one can get the following expression

$$\theta_{pole}=\sin^{-1}\sqrt{R_*/R_A}\ , \text{ or } \theta_{pole} \approx \sqrt{R_*/R_A}$$

For typical values of neutron star parameters R_*=10 km and R_A =1000 km the half angle comes out to be θ_{pole} =1/10 radians. The polar cap radius $R_{pole}=R_* \sin(\theta_{pole}) \approx R_* \theta_{pole}$) then can be estimated to be $R_{pole} \approx$ 1 km.

Height of the Accretion Column

The height of the accretion column and the physical state of matter and radiation inside the accretion column are determined by the types of shocks (radiative, collisionless and collisional shocks) and will be described next. In a milestone work, Basko and Sunyaev (1976) studied the flow of matter in the polar cap region and noted that the possibility of radiative shock formation is highly increased if the luminosity exceeds the critical value L^* Local Eddington Luminosity)

$$L^* = \left(\frac{GM_* m_H}{\sigma_\parallel}\right)\frac{A_{pole}}{R_*^2} \qquad 2.5$$

where $A_{pole} = \pi\ R_{pole}^2$ is area of base of accretion column and $\sigma_\parallel$ is the magneto Compton cross-section (photon-electron cross-section in high magnetic field) parallel to the magnetic field.

G is the gravitational constant M_*, R_* are the mass of the neutron star and radius of the neutron star respectively, m_H is mass of the hydrogen atom. Assuming $\sigma_\parallel$ = σ_T (σ_T is the Thompson scattering cross-section = 6.6 X 10^{25} cm^2) and for the typical neutron star parameters stated above, the value of the critical luminosity is of the order of 10^{36} erg s^{-1}.

In several other works the physics of shock formation had been studied (Wang and Frank (1981), Langer and Rappaport (1982), Meszaros et al. (1983), Harding et al. (1984), Pakey (1990), Karino et al.

(2007), Becker et al. (2012)). The essence of some of these works will be discussed next.

Height Dependence on Luminosity

The highly magnetized accreting X-ray pulsars can be classified depending upon the luminosity ranges:

1. High luminosity sources 10^{37-38} erg s^{-1}
2. intermediate luminosity sources 10^{36-37} erg s^{-1}
3. Low luminosity 10^{35-36} erg s^{-1}

High Luminosity X-ray Pulsars

In case of high luminosity sources 10^{37-38} erg s^{-1} (L >> L*) the radiation has strong effect on the flow of the infalling matter near the neutron star surface. In these sources the radiation flux removes the energy of electrons in the infalling material and hence the flow is decelerated in a radiative shock, a few kilometers above the neutron star's surface. When the gas passes through the radiative shock its bulk velocity drops by a factor of 7 in the post shock region, after which the matter is further decelerated by radiation throughout its passage from the shock to the neutron star surface. The infalling matter finally lands smoothly on the neutron star surface. The column is optically thick $\tau_T>1$ (τ_T is the Thompson optical depth) across the channel and $\tau_T >> 1$ along the channel hence the radiation comes out from the optically thin layers of side walls of the accretion column, this geometry being called the fan beam geometry. The height of the shock increases (up to a limiting height or up to the Alfven radius) with increasing luminosity since due to high optical depth, radiation can only manage to carry away the energy if the height of the column increases providing more surface area at the sides for the radiation to escape.

Intermediate Luminosity X-ray Pulsars

In the intermediate luminosity sources (10^{36-37} erg s^{-1}) the matter is decelerated by the radiation pressure first at the radiative shock, then further in the post shock region. However, the final deceleration of the matter occurs by Coulombic collisions in the atmosphere of neutron star (Nelson et al. 1993). In these sources the radiation escapes sideways (fan beam geometry) as well as along the column (pencil beam geometry), creating a mixed fan cum pencil beam geometry.

Low Luminosity X-ray Pulsars

In low luminosity sources L << L* $=10^{36}$ erg s^{-1} the infalling matter avoids the formation of radiative shocks. In these circumstances either the collisionless or collisional shocks (or neither) form. The collisionless shock may form if the plasma instabilities occur similar to two-stream instabilities in zero magnetic field case. Assuming that such collisionless shocks may form, the properties of the post shock column has been studied by Langer and Rappaport (1982). The scale height of the shock may be as large as $h=1.5\ R_*$ and increases with decreasing B and $\dot{M}$ (accretion rate). As the $\dot{M}$ decreases, n_e (electron number density) decreases and the cooling time which is proportional to $1/\ n_e$ increases, so a larger volume is needed by the gas to radiate energy.

The shock transition region is very thin, of the order of gyroradius. Due to the jump condition at the shock the density increases four-fold and the velocity decreases by a factor of 4. In the absence of collisionless shocks the other possibility to stop the flow is collisional shocks due to electron-proton and proton-proton collisions in accretion column.

Since electrons populate mostly the Landau ground state in high field ($B>10^{12}G$) low density regime ($n_e < 10^{21}\ cm^{-3}$) their motion is practically linear along the magnetic field lines. These electrons are capable of stopping the protons by many small angle collisions. These highly anisotropic electron-proton scatterings have higher stopping length than proton-proton scatterings when the electron temperature is close to 10 keV and electron number $n_e < 10^{23}\ cm^{-3}$ (Pakey (1990)). Harding et al. (1984) have studied the stopping of material by Coulombic interaction in a self consisting model. They found that the Coulomb heated column is a thin slab with scale height of 1 - 200 cm and most of the radiation escapes from the top since the optical depth is 1000 times greater along the sides of the slab. The densities are quite high near the base: $n_e \sim 10^{22} - 10^{24}\ cm^{-3}$.

From the above discussion it may be concluded that even for the low luminosity sources (L << L* = 10^{36} erg s^{-1}) two type of geometries are possible: in case of collisonless shocks a cylindrical type (height of few kilometers) and in case of Coulomb collisions a slab type with scale height of a few meters.

Conclusion

Neutron stars are very exotic stellar objects which posses very high magnetic fields. In a binary system they accretes material from a companion star. The material is captured from companion star at accretion captured radius $R_G \approx 10^5$ km, then the flow is disrupted at alfven radius $R_A \approx 10^3$ km. The plasma flows along the magnetic field lines and forms accretion column on magnetic poles of neutron star. Calculations show that radius of the base of accretion column comes out to be as 1 km. Height of the accretion column depends upon luminosity of X-ray pulsar. Height of the accretion column is largest in case of High luminosity sources, medium in intermediate luminosity sources and height of the accretion column is very small in low luminosity sources.

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