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# Magnetocavitation mechanism for the generation of plasma ejection from the accreting neutron star

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The process of plasma ejection generation from the accreting neutron star is studied. Magnetocavitation mechanism as the possible mechanism of this process is proposed. According to this mechanism, the plasma ejection is produced because of the magnetospheric destruction associated with processes of the neutron star quake, resonant interaction of the magnetosphere with accreted plasma and actions of shock waves from the accretion disk of the neutron star. The suggested mechanism sets some limits on the ejection parameters, however, the estimations of the ejection parameters performed in this research are consistent with observations.

*Keywords*: Neutron stars, ejections, magnetic reconnection

## 1 Introduction

Jets and ejections are observed in many astrophysical objects: X-ray binary stars, microquasars, young stellar objects, proto-planetary nebulae, active galactic nuclei, supernovae, sources of gamma ray bursts, and the Sun (Priest & Forbs (2005); Beskin (2010)). Although ejections are short-lived plasma outflows erupting from the objects from time to time, and jets are considered to be collimated plasma outflows that exist for a long time, ejections and jets are usually named as jets.

Various mechanisms of jet formation were proposed (Shklovsky (1963); Kardashev (1964); Bisnovatyi-Kogan et al. (1969); Blandford & Rees (1974); Blandford (1976); Blandford & Znajek (1977); Blandford & Payne (1982); Beskin (2009, 2010)). However as a whole the nature of jets is still far from understood. In particular, we do not know the mechanism of jet generation from accreting neutron stars with an extremely strong magnetic field of $\sim 10^{14}$–$10^{16}$ Oe named usually soft gamma repeaters. It is thought that the activity of soft gamma repeaters is connected with energy reserved in their magnetic field (Mereheti et al. (2015)). During the activity part of this energy can transform into the energy of soft gamma radiation and kinetic energy of plasma ejections. It is necessary to remember about the magnetocavitation

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mechanism proposed earlier as an explanation of gamma ray bursts (Gnedin & Kiikov (2000)). According to this mechanism, a gamma ray burst energy source is the energy of the magnetized vacuum bubble around a neutron star (Gnedin & Kiikov (2000)). The idea of this mechanism is based on the analogy of the sonoluminescence phenomenon arising at the collapse of gas bubbles in the fluid which is accompanied by jet formation (Katz (1996)). In this case the collapse of the magnetized bubble playing the role of the magnetosphere is considered. The destruction of the magnetosphere is due to the resonant phenomena that results from the interaction of the magnetosphere with accreted plasma. The behavior of the magnetosphere in accreted plasma is similar to the behavior of the gaseous bubble in the fluid, therefore the model describing the magnetosphere behavior was called the magnetocavitation model (Gnedin & Kiikov (2001)).

The idea of jet formation as a result of a magnetosphere collapse was mentioned in the work of Gnedin and Kiikov (Gnedin & Kiikov (2000)). Based on the analogy of the outflow formation at the collapse of a bubble in a fluid, this paper proposes the magnetocavitation model for plasma ejection formation from the accreting neutron star.

## 2 Basic equation of magnetocavitation mechanism

According to the magnetocavitation mechanism, the magnetosphere of an accreting neutron star is treated as a magnetized gaseous cavity, and the accreting plasma is considered as an incompressible fluid. The basis of this mechanism is the equation obtained earlier in the study of the quasiperiodic oscillations of X-ray radiation of accreting neutron stars (Gnedin & Kiikov (2001)). Assuming that plasma is in rest far from a neutron star, and neglecting the effects of the viscosity and gravitation, this equation can be written as:

$$R\frac{dR}{dt}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2=\frac{\Delta p}{\rho}, \tag{1}$$

where $t$ is time; $\rho$ and $p$ are the density and pressure of accreted plasma, respectively; $R$ is the magnetospheric radius; $\Delta p = H^2/(8\pi) - p$; $H$ is the magnetic field strength at the Alfvén surface. Equation (1) describes nonlinear changes of the magnetospheric radius. In the case when $\Delta p > 0$, the magnetosphere expands, and at the condition $\Delta p < 0$, it contracts. The processes of the neutron star quake, resonant interaction of the magnetosphere with accreted plasma and actions of the shock waves from the accretion disk of the neutron star can promote the strong changes of $\Delta p$ and $R$ that in turn leads to the magnetosphere collapse because of the instability of the magnetic field configuration.

## 3 Estimations of the plasma ejection parameters

Assuming that $\Delta p = \text{const}$, and integrating equation (1), we have:

$$\left(\frac{dR}{dt}\right)^2=-\frac{2}{3}\frac{\Delta p}{\rho}\left(\frac{R_0^3}{R^3}-1\right)$$

or

$$v^2 = -\frac{2}{3}\frac{\Delta p}{\rho}\left(\frac{R_0^3}{R^3} - 1\right), \tag{2}$$

where $v = \dfrac{dR}{dt}$ is the radial velocity of accreted plasma; $R_0$ is the magnetospheric radius at equilibrium time.

Then under conditions $\Delta p < 0$, $R \to 0$ (the magnetosphere contracts), from relation (2) we get:

$$v \approx \left(-\frac{2}{3}\frac{\Delta p}{\rho}\frac{R_0^3}{R^3}\right)^{\frac{1}{2}}. \tag{3}$$

In the case at $\dfrac{H^2}{8\pi} \ll p$, taking into account (3), we can obtain the following estimations for the magnetospheric radius, contraction velocity and pressure of accreted plasma, respectively:

$$R \sim \frac{L^{\frac{1}{5}}}{\rho}t^{\frac{3}{5}} \sim \frac{E^{\frac{1}{5}}}{\rho}t^{\frac{2}{5}}, \tag{4}$$

$$v \sim \frac{L^{\frac{1}{5}}}{\rho}t^{\frac{-2}{5}} \sim \frac{E^{\frac{1}{5}}}{\rho}t^{\frac{-3}{5}}, \tag{5}$$

$$p \sim \frac{Lt}{R^3} \sim \frac{E}{R^3}, \tag{6}$$

where $E$ is the kinetic energy released during the magnetosphere contraction, $L$ is the luminosity. If $t \to 0$, we have $v \to \infty$, but it is not possible. This means we cannot apply relation (5) to investigate the magnetosphere behavior at an arbitrary time moment. Moreover the magnetosphere cannot contract permanently because the magnetic pressure increases during its contraction. So there is a limit on the magnetosphere contraction in the considered model. However the magnetosphere contraction to a certain limit can lead to the fast change of the magnetic field configuration that will be accompanied by processes of the magnetic reconnection and generation of the plasma ejection that is similar to the corona ejections of the plasmoids on the Sun. Thus the magnetosphere will collapse. The velocity $v_{ej}$ of the plasma ejection generated due to the magnetic reconnection can be defined by the estimation (Priest & Forbs (2005)):

$$v_{ej} \sim \frac{H}{\sqrt{\rho}} \sim v_A, \tag{7}$$

where $v_A$ is Alfvén velocity.

Using (2), and taking into account that $R \to 0$ (the magnetosphere contracts), we obtain the approximate formula for the time of the collapse:

$$t \approx 0.915 R_0 \sqrt{\frac{\rho}{p_0}}, \tag{8}$$

where $p_0$ is the pressure of accreted plasma at equilibrium time. Supposing $E \sim 10^{41}$ Erg, $R_0 \sim 10^{10}$ cm, $\rho \sim 10^{-9}$g cm$^{-3}$, from (8) we get $t \sim R_0\sqrt{\dfrac{\rho}{p_0}} \sim R_0^2\sqrt{\dfrac{\rho R_0}{E}} =$

$10^{20}\sqrt{\frac{10^{-9}10^{10}}{10^{41}}} = 1$ s, that agrees with the duration of short gamma-bursts from the soft gamma repeaters in our Galaxy.

Now let us consider the case when $\Delta p > 0$ and $R \to \infty$ (the magnetosphere expands). Then from (2) we have:

$$v \approx \left(\frac{2}{3}\frac{\Delta p}{\rho}\right)^{\frac{1}{2}}. \tag{9}$$

If $\frac{H^2}{8\pi} \gg p$, taking into consideration (9), we can get the following estimations for the magnetospheric radius and the velocity of the magnetosphere expansion, respectively:

$$R \sim \frac{H}{\sqrt{\rho}}t, \tag{10}$$

$$v \sim \frac{H}{\sqrt{\rho}} \sim \left(\frac{E}{\rho R^3}\right)^{\frac{1}{2}} \sim \left(\frac{Lt}{\rho R^3}\right)^{\frac{1}{2}} \sim v_A. \tag{11}$$

The magnetosphere expansion can lead to the change of the magnetic field configuration owing to the processes of the star quake, interaction with accreted plasma and shock waves from the accretion disk. Therefore the magnetosphere will be destroyed again. The magnetic reconnection and generation of plasma ejection will be produced.

Comparing (7) and (11), we have $v \sim v_{ej}$. Let the magnetic field of the accreting neutron star be a dipole. Then for the soft gamma repeater with the magnetic field strength $H_s = 10^{15}$ Oe, the radius of the neutron star $R_s = 10^6$ cm and $R_0 = 10^9$ cm we find from the relation $HR_0^3 = H_sR_s^3$ that the magnetic field strength at the Alfvén surface is $H \sim 10^6$ Oe. For $\rho \sim 10^{-8}$g cm$^{-3}$ and $H \sim 10^6$ Oe from (11) we have the following value of the velocity of the magnetosphere expansion (or contraction): $v \sim \frac{10^6}{\sqrt{10^{-8}}} = 10^{10}$cm/s $\sim c$, where $c$ is the light velocity. The obtained result is in good accordance with the observations. If the neutron star is typical, $H_s = 10^{12}$ Oe, $R_s = 10^6$ cm, $R_0 = 10^8$ cm, we get the same result.

It will be noticed that the suggested mechanism can provide an explanation for jet acceleration. If the accreting neutron star has a jet, this initial jet can be accelerated by the plasma ejection generated as a result of magnetosphere destruction.

## 4 Discussion

The magnetic field configuration in the magnetosphere of a neutron star depends on the accretion rate and the regime of the interaction with accreted plasma, the intensities of the neutron star quake and shock waves from the accretion disk. In the cases of negligible variations of the accretion rate and non-resonant interaction with accreted plasma, the weak quakes of the neutron star and shock waves, the magnetosphere of the neutron star oscillates and it can lead to quasiperiodic oscillations of X-ray radiation of the neutron star (Gnedin & Kiikov (2001)). In the contrary cases, the

magnetosphere of the neutron star is unstable and is destroyed, the magnetic field quickly changes its configuration, the magnetic reconnection and the plasma ejection are produced. During this process, part of the magnetic energy is transformed into the kinetic energy of ejected plasma. The values of this energy and other parameters of the ejection correspond to the values estimated from observations. If we take into account the energy of the magnetized vacuum, the magnetocavitation mechanism can also explain gamma ray bursts (Gnedin & Kiikov (2000)).

## 5 Conclusions

Thus from the magnetocavitation mechanism considered here we have the following results: the magnetosphere of the accreting neutron star can be destroyed during its contraction or expansion; the magnetosphere destruction leads to the plasma ejection generation from the accreting neutron star; the estimations of the ejection parameters are in accordance with the observational data (bursts of soft gamma repeaters); velocity of plasma ejection is an order of Alfvén velocity; the plasma ejection can accelerate an initial jet of the accreting neutron star; this mechanism puts some restrictions on the parameters of the plasma ejection.

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