Accretion by Isolated Neutron Stars

1 Introduction

As a neutron star moves through the interstellar medium it interacts in a time unit with the mass
\[ M_0 \simeq 10^9 \text{ g s}^{-1} n m^2 \left( \frac{V_{\text{rel}}}{10^7 \text{ cm s}^{-1}} \right)^{-3}, \]
where \( m \) is the mass of the neutron star expressed in units of \( 1.4 M_\odot \), \( n \) is the number density of material situated beyond the accretion (Bondi) radius of the star expressed in units of 1 hydrogen atom cm\(^{-3}\) and \( V_{\text{rel}} \) is the relative velocity between the star and its environment, which is limited to the sound speed in the interstellar material as \( V_{\text{rel}} > V_0 \). The mass capture rate by the star from its environment is therefore limited to \( \dot{M}_c \leq M_0 \).

A necessary condition for the captured material to reach the stellar surface is
\[ r_m < r_{\text{cor}}, \]
where
\[ r_m = \left( \frac{\mu^2}{2GM_{\text{ns}} c^2} \right)^{2/7}, \]
is the magnetospheric radius of a neutron star, and
\[ r_{\text{cor}} = \left( \frac{GM_{\text{ns}} P_s^2}{4\pi^2} \right)^{1/3}, \]
is its corotational radius. Here \( \mu, M_{\text{ns}} \) and \( P_s \) are the dipole magnetic moment, mass and spin period of the star, and \( G \) is the gravitational constant. Solving the inequality \( 7 \) for \( P_s \) one finds
\[ P_s > P_{\text{cd}} \simeq 7000 \text{ s} \times \left( \frac{\mu_{30}}{10^{39} \text{ G cm}^3} \right)^{6/7} V_7^{9/7} n^{-3/7} m^{-11/7}, \]
where \( \mu_{30} = \mu/10^{39} \text{ G cm}^3 \). This implies that the spin-down rate of the neutron star in a previous epoch was
\[ \dot{P} > 10^{-14} \left( \frac{P_s}{7000 \text{ s}} \right) \left( \frac{t_{\text{sd}}}{10^{10} \text{ yr}} \right)^{-1} \text{ s s}^{-1}, \]
and therefore, suggests that only the stars whose initial dipole magnetic moment was in excess of \( 10^{39} \text{ G cm}^3 \) could be a subject of further consideration (for a discussion see, e.g., [Popov et al. 2000a]). Here \( t_{\text{sd}} \) is the spin-down timescale of the neutron star.

Finally, a formation of an accretion disk around the magnetosphere of an isolated neutron star accreting material from the interstellar medium could be expected only if the relative velocity satisfies the condition \( V_{\text{rel}} < V_0 \), where
\[ V_0 \simeq 10^5 \text{ cm s}^{-1} \left( \frac{V_{\text{cd}}}{10^6 \text{ cm s}^{-1}} \right)^{-6/5} \left( \frac{R_s}{10^{20} \text{ cm}} \right)^{-7/5} \]

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Here $V_t$ is the velocity of turbulent motions of the interstellar material at a scale of $R_0$ and the Kolmogorov spectrum of the turbulent motions is assumed (Prokhorov, Ponson & Khodakevich 2002). This inequality, however, can unlikely be satisfied since $V_0$ is smaller than the speed of sound in the interstellar material, and therefore, is smaller than the lower limit to $V_{rel}$.

Thus, the accretion by old isolated neutron stars can be treated in terms of a spherical (Bondi) accretion onto a magnetized, slowly rotating neutron star. The accretion picture under these conditions has been reconstructed first by Arons & Lea (1976) and Elsner & Lamb (1976) and further developed by Lamb et al. (1977) and Elsner & Lamb (1984). An application of the results reported in these papers to the case of an isolated neutron star is discussed in the following sections.

2 Accretion flow at $r_m$

As shown by Arons & Lea (1976) and Elsner & Lamb (1976), the magnetosphere of a neutron star undergoing spherically symmetrical accretion is closed and, in the first approximation, prevents the accretion flow from reaching the stellar surface. The mass accretion rate onto the stellar surface is therefore limited to the rate of plasma entry into the magnetosphere. The fastest modes by which the material stored over the magnetospheric boundary can enter the stellar magnetic field are the Bohm diffusion and interchange instabilities (Elsner & Lamb 1984).

The rate of plasma diffusion in the considered case can be evaluated as (Ikhsanov 2003)

$$\dot{M}_B \leq 2 \times 10^6 \text{g s}^{-1} \zeta_{0.1}^{1/2} \mu_{30}^{-1/14} n_{11}^{15/7} V_7^{33/14} r_6^{-1},$$

where $\zeta_{0.1} = \zeta/0.1$ is the efficiency of the diffusion process normalized according to Gosling et al. (1991). This indicates that the luminosity of the diffusion-driven source is limited to

$$L_{x,d} \leq 4 \times 10^{36} \text{erg s}^{-1} \times \zeta_{0.1}^{1/2} \mu_{30}^{-1/14} n_{11}^{22/7} V_7^{33/14} r_6^{-1}.$$

For the material to enter the stellar magnetic field with the rate $\sim \dot{M}_c$, the boundary should be interchange unstable. The onset condition for the instabilities is (Arons & Lea 1976; Elsner & Lamb 1976)

$$T_p(r_m) \leq 0.1 T_H(r_m),$$

where $T_p(r_m)$ and $T_H(r_m)$ are the plasma temperature and the free-fall (adiabatic) temperature at the magnetospheric boundary, respectively. This indicates that a direct accretion of the captured material onto the stellar surface could occur only if the cooling of the plasma at the boundary dominates the heating.

The mechanism which is responsible for the cooling of plasma at the boundary is the bremsstrahlung emission (Klemeš 1961) and the free-fall temperature and number density of the material stored over the boundary are, respectively,

$$r_m \simeq 6 \times 10^{10} \text{cm} \times \mu_{30}^{4/7} n_0^{-2/7} m^{-1/7},$$

$$T_H(r_m) \simeq 10^7 K \times \mu_{30}^{-4/7} n_0^{2/7} m^{6/7},$$

$$N_c(r_m) \simeq 300 \text{cm}^{-3} \times \mu_{30}^{-6/7} m^{-10/7} m^{-2/7}.$$  

Under these conditions both the cyclotron and Compton cooling time scale are significantly larger than the bremsstrahlung cooling time scale

$$t_{br}(r_m) \simeq 10^5 \text{yr} \times T_7^{1/2} \left( \frac{N_c(r_m)}{300 \text{ cm}^{-3}} \right)^{-1},$$

where $T_7 = T_H(r_m)/10^7 K$.

The heating of the material at the magnetospheric boundary is governed by the following processes.

2.1 Adiabatic shock

As the captured material reaches the boundary it stops in an adiabatic shock. The temperature in the shock increases to $T_H(r_m)$ on a dynamical time scale,

$$t_H(r_m) \simeq 7 \times 10^4 \text{s} \times m^{-1/2} \left( \frac{r_m}{6 \times 10^{10} \text{cm}} \right)^{3/2}.$$  

Since $t_H(r_m) \ll t_{br}(r_m)$ the height of the homogeneous atmosphere at the boundary proves to be $\sim r_m$. This prevents an accumulation of material over the boundary. Furthermore, as the condition $t_H(r_G) < t_{br}(r_m)$ is satisfied throughout the gravitational radius of the neutron star a hot quasi-stationary envelope extended from $r_m$ up to $r_G$ forms (Davies & Pringle 1981). The formation of the envelope prevents the surrounding material from penetrating to within the gravitational radius of the neutron star. The mass of the envelope is, therefore, conserved. As the neutron star moves through the interstellar medium the surrounding material overflow the outer edge of the envelope with a rate $\dot{M}_c$.

Within an approximation of a non-rotating star whose “magnetic gate” at the boundary is closed completely the envelope remains in a stationary state on a time scale of $t_{br}(r_m)$. As the condition $t_H(r_m)$ is satisfied the boundary becomes unstable and material enters into the magnetic field and accretes onto the stellar surface with a rate of $\sim \dot{M}_c$. As shown by Lamb et al. (1977), the time of the accretion event in this case is limited to $t_{\text{burst}} < a few \times t_H(r_m)$ during which the temperature of the envelope increases again to the adiabatic temperature (as...
the upper layers of the envelope comes to 

\[ L_{\text{burst}} \simeq 2 \times 10^{29} n V_{7}^{-3} m^{3} r_{6}^{-1} \text{ erg s}^{-1}, \]  

(16)

the typical outburst durations of \( t_{\text{burst}} \leq 30 \text{ min} \) and the repetition time of \( t_{\text{rep}} \sim t_{\text{br}}(r_{m}) \sim 10^{5} \text{ yr}. \)

2.2 Subsonic propeller

As shown by Davies & Pringle (1981), the rotation of a neutron star surrounded by the hot envelope can be neglected only if its spin period exceeds (Ikhsanov 2001)

\[ P_{\text{br}} \simeq 10^{5} s \times \mu_{30}^{16/21} n^{-5/7} V_{7}^{15/7} m^{-34/21}. \]  

(17)

Otherwise, the heating of plasma at the inner edge of the envelope due to propeller action by the star dominates cooling. The corresponding state of the neutron star is referred to as a subsonic propeller. The star remains in this state as long as its spin period satisfies the condition \( P_{\text{cd}} < P_{r} < P_{\text{br}}. \) The time during which the spin period increases from \( P_{\text{cd}} \) up to \( P_{\text{br}} \) is

\[ \tau_{\text{br}} \simeq 2 \times 10^{5} \text{ yr} \times \mu_{30}^{-2} I_{45} m \left( \frac{P_{\text{br}}}{10^{9} \text{ yr}} \right), \]  

(18)

where \( I_{45} \) is the moment of inertia of the neutron star expressed in units of \( 10^{45} \text{ g cm}^{2}. \) This indicates that the spin periods of accreting isolated neutron stars are expected to be in excess of a day, and therefore, these objects can unlikely be recognized as pulsars.

2.3 Diffusion-driven accretor

As mentioned above, the “magnetic gate” at the magnetospheric boundary is not closed completely. The plasma flow through the interchange stable boundary is governed by the diffusion. As shown by Ikhsanov (2002), this leads to a drift of the envelope material towards the star and, as a result, to an additional energy source for heating of the envelope material. The heating due to the radial drift dominates the bremsstrahlung energy losses from the envelope if

\[ \mathcal{M}_{\text{c}} \lesssim 10^{14} \text{ g s}^{-1} \times \mu_{30}^{7/17} n_{0,1}^{-1/17} V_{7}^{14/17} m_{16/17}. \]  

(19)

This indicates that only the isolated neutron stars which move slowly \( (V_{\text{cd}} \ll 10^{7} \text{ cm s}^{-1}) \) through a dense molecular cloud \( (N_{c} > 10 \text{ cm}^{-3}) \) can be expected to be observed as the bursters. The rest of the population would appear as persistent X-ray sources with the luminosity of \( L_{x} \leq L_{x,\text{dd}} \) (see Eq. 4).

3 Discussion

The results of this paper force us to reconsider previously made predictions about the number of old isolated neutron stars which could be observed with recent and current X-ray missions. In particular, the total flux of the persistent emission of these objects within the above presented accretion scenario is limited to \( F \leq 10^{-16} \text{ erg cm}^{2} \text{ s}^{-1} d_{100}^{-2} \), where \( d_{100} \) is the distance to the source expressed in units of 100 pc. Furthermore, the mean energy of photons emitted by these objects within the blackbody approximation is close to 50 eV. This clearly shows that a detection of these sources by the Chandra and XMM-Newton is impossible.

The X-ray flux emitted by the accreting isolated neutron stars during the outbursts (see Sect. 2.1) is over the threshold of sensitivity of modern detectors. However, the probability to detect this event appears to be negligibly small. Indeed, the number of these sources which could be detected by Chandra and XMM-Newton is

\[ N \leq 10^{-5} \left( \frac{N(0)}{3 \times 10^{4}} \right) \left( \frac{t_{\text{burst}}}{30 \text{ min}} \right) \left( \frac{t_{\text{rep}}}{10^{5} \text{ yr}} \right), \]  

(20)

where \( N(0) \) is the number of the sources which would be observed if the influence of the stellar magnetic field to the accretion flow at \( r_{m} \) were insignificant (Popov et al. 2000).

Our results, therefore, naturally explain a lack of success in searching for the isolated neutron stars accreting material from the interstellar medium. They rather suggest that these objects can be considered as targets for coming space missions with more sensitive detectors in the soft X-ray part of the spectrum.

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