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Why the Number of Galactic X-Ray Stars Is So Small?

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Summary. The number of galactic X-ray sources is by $4 \div 7$ orders of magnitude less than the expected number of neutron stars and black holes in binary systems. It is shown in the paper that the main condition for the appearance of X-ray source in a binary system including relativistic star is that the size of the normal component must be close to size of its critical Roche lobe.

In the case of accretion of the stellar wind matter in detached binary system the specific angular momentum of the matter captured by the relativistic star is small. Therefore the accreting disk is not formed around relativistic star. Consequently, a *black hole* in detached binary system can not be strong X-ray source (no matter how strong the stellar wind might be). In this case the accretion is spherically-symmetric and black hole is the source of hard X-ray and γ-ray radiation.

Young *neutron star* in detached system is ejecting pulsar, radiating in X-ray spectral band, like the Crab pulsar. Its radioemission is absorbed in stellar wind plasma due to free-free processes. Deceleration of the pulsar rotation and connected decrease of its luminosity makes possible the penetration of the ambient plasma inside light cylinder. This may lead to the switching off of the pulsar mechanism. However rapidly rotating magnetosphere of the neutron star throws away the falling matter, preventing the accretion. The rotation, consequently, continues to decelerate. Only after sufficient deceleration of neutron star rotation the accretion becomes possible and neutron star will be the X-ray source. However the estimates show that the deceleration time up to this stage exceeds the evolutionary time of the normal component. Only in the extremely close binaries having anomalously strong accreting matter flow it is possible for the magnetized neutron star to convert into the X-ray sources.

For the same reason old single pulsars with strong magnetic field never become the sources of ultra-violet and soft X-ray radiation.

Key words: black holes and neutron stars — accretion — X-ray sources — pulsars

I. The General Picture

According to the UHURU satellite data the number of the galactic X-ray sources is about 100, many of them are variable on a time scale less than a day and are X-ray stars (Giacconi *et al.*, 1974). It is likely that the majority of the X-ray stars are components of close binary systems. They are probably neutron stars or black holes and emit X-rays owing to accretion of the gas flowing from the normal star.

On the other hand more than a half of a total number of stars are components of binary systems (Martynov, 1971); the theory of stellar evolution predicts the existence of a great $(10^7 \div 10^9)$ number of neutron stars and black holes in the Galaxy (Zeldovich and Novikov, 1971). Many stars lose the matter intensively (Pottasch, 1970). At the same time the probability of the disruption of the binary system during the supernova explosion is not extremely high.

One might think then, that the number of the X-ray sources, radiating owing to accretion should be of the same order of magnitude as the total number of neutron stars and black holes in the Galaxy. This conclusion obviously contradicts to the observational data.

In this article, we have tried to find the reason of this contradiction. It is shown below that the binary system including the relativistic object, may become a powerful source of X-ray radiation in the classical $1 \div 10$ keV spectral band only in case, when it is close and the size of its normal component is about the size of the critical Roche lobe. Note, that the normal components of all the investigated binary X-ray systems, are evidently close to the filling of their critical Roche lobes.

For this very reason, their subdivision into two classes is clearly observed: O and B supergiants (normal components of Cyg X 1, Cen X 3, 3 U 0900-40, SMC X 1 3 U 1700-37), which have the size of the order of the Roche lobe size and 2) subgiants of the late-type spectral class (Her X 1, Sco X 1, Cyg X 2), which have left the main sequence and have filled their critical Roche lobe for a short period of time (Gursky and Schreier, 1974; Sunyaev and Shakura, 1974). Obviously, the total

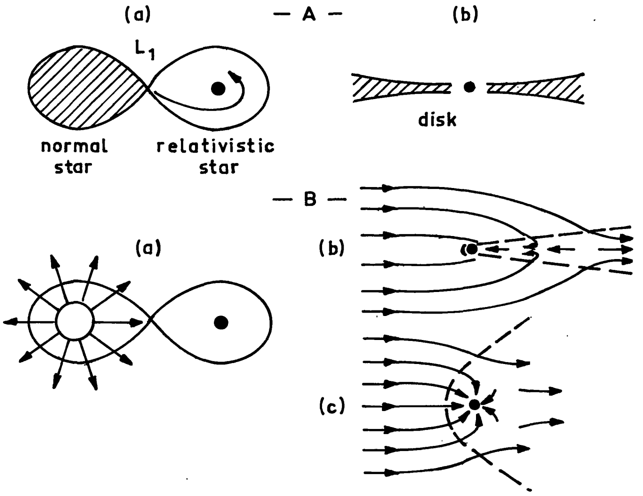

Fig. 1A and B. Three types of the accretion picture on the relativistic star in the binary system. (A) Semidetached system (a) normal component fills up its critical Roche lobe, the outflow of matter takes place through the inner lagrangian point (b) the accreting matter has a great angular momentum and forms the disk aroung the relativistic object which radiates X-rays. (B) Detached system (a) the size of normal star is small in comparison with the critical Roche lobe, the mass loss is associated with stellar wind; (b) the great rate of accretion: the matter behind the shock wave loses its thermal energy due to free-free radiation; the main part of captured matter has small angular momentum and falls onto the relativistic star in the narrow cone and forms the dense stream with relatively low temperature (c) the small rate of accretion; the collisionless and emissionless bow-shock wave is formed. The fall of the matter obeys the laws of the spherically-symmetric accretion. The accreting matter has a magnetic field, high temperature and radiates in hard X and γ-rays

number of neutron stars and black holes in binaries is immense and considerably exceeds the number of galactic X-ray sources. One should discover these objects applying some other methods and primarily with the help of the detection of hard X-ray and γ-radiation (Illarionov and Sunyaev, 1975a), investigating spectroscopic binaries, where only one component is observed (Zeldovich and Guseynov, 1965); observing tidal distortion of a normal component and its periodical light-curve (Efremov *et al.*, 1974); or rapid fluctuations of radio and optical radiation. Close binaries including black holes, at a small rate of accretion, may be weak sources $L \sim 10^{33} \div 10^{36}$ erg/s of soft X-ray and ultraviolet radiation (Shakura and Sunyaev, 1973).

A. Accretion in Semicontact Systems

The problem of relativistic objects in semi-contact binary systems has been rather well investigated; the outflow of matter through the inner lagrangian point leads to the formation of the disk of matter, accreting onto a relativistic object. The release of gravitational energy in the disk and (in the case of a neutron star or a white dwarf) on the surface of a relativistic object leads to the heating of accreting matter up to high temperatures and to X-ray emission (Prendergast and Burbidge, 1968; Shakura, 1972; Pringle and Rees, 1972; Shakura and Sunyaev, 1973) (Fig. 1A). Note, that the temperature of the inner parts of the disk is the strong function of its luminosity (accretion rate). When the rate of accretion is small, the main part of the energy released is radiated into an ultraviolet spectral band inaccessible to direct observations. The accreting disk is an X-ray source only when its luminosity is high $L_x \sim 10^{37} \div 10^{39}$ erg/s (Shakura and Sunyaev, 1973). This appears to be one of the reasons of absence in the Galaxy of a great number of weak X-ray sources (Giacconi *et al.*, 1974).

B. Accretion in Detached Binaries

This paper deals mainly with the accretion onto a relativistic object in detached binaries, where the matter outflows from the normal component in the stellar wind. The velocity of the stellar wind V_0 considerably exceeds orbital velocities $V_{\rm orb}$ of components in a binary (Fig. 1B). As a consequence of the condition $V_{\rm orb} \ll V_0$, the small ratio of the accretion rate onto a relativistic object $\mathscr{\dot{M}}$ to the rate of mass loss by a normal component $\dot{M}$ is the peculiarity of accretion in a detached binary system [see Eq. (3)].

a) Black Holes

It will be shown in this paper that the accreting disk (responsible for X-ray radiation) is formed around the black hole if only the size of the normal star is close to that of the limiting Roche lobe, and matter is flowing mainly through the inner Lagrangian point.
In the alternative case of the accretion of stellar wind (no matter how strong it might be) in a detached system, the angular momentum of accreting matter captured by a black hole is less than $\sqrt{3}r_g c$ per unit mass, which is not enough for the disk to be formed. Recall that $\sqrt{3}r_g c$ is a specific angular momentum of a matter on the last stable orbit $r = 3r_g$ around Schwarzschild black hole. Here and below $r_g = \frac{2GM_r}{c^2}$ is the gravitational radius of a black hole.

b) Black Hole as a γ-ray Source

The accretion onto a black hole in a detached binary system adheres to the laws of spherically-symmetric accretion. The difference from the usually considered case of the single black hole (Schwartzman, 1971a; Shapiro, 1973; Bisnovatyi-Kogan and Ruzmaikin, 1974) is connected with the possibility of considerable $\mathscr{\dot{M}} \sim 10^{-11} \div 10^{-8} M_\odot$/year rate of matter accretion onto a black hole in a binary system including a normal component with intensive stellar wind. As a consequence, the density of the accreting matter in a relativistic region is much greater.
The analysis carried out in another our paper (Illarionov and Sunyaev, 1975a) shows that when the rate of

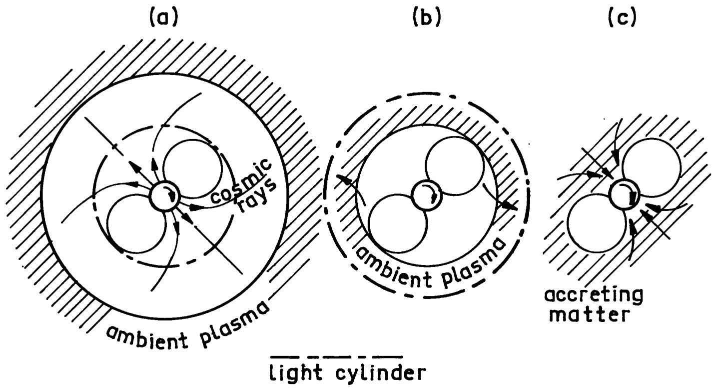

Fig. 2a–c. Three possible stages in the life of neutron star in the detached binary system (a) young ejecting radiopulsar—the sourse of cosmic rays, X-rays and pulsed optical radiation; the radioemission is absorbed in the stellar wind plasma (b) the power of the pulsar decreases and the plasma of the stellar wind becomes to penetrate under the light cylinder. However the magnetosphere corotating with the neutron star does not permit the accretion on the surface, throwing away the accreting matter. In this stage the neutron star acts as a "propeller". (c) the period of neutron star is strongly increased, the stellar wind plasma accretes to the regions of magnetic poles: the neutron star becomes the accreting source of pulsed X-ray radiation

accretion is great, the black hole in a detached binary must be a powerful stationary source of γ-radiation in the range $10 \div 200$ MeV. This γ-radiation is connected with a decay of π°-mesons, which are born in collisions of the high-temperature accreting protons. The efficiency of accretion onto a black hole (the ratio of the escaped radiation energy to the rest energy of accreting matter) obviously grows linearly with the increase of the rate of accretion. It may reach 1% for rates of accretion of the order of $10^{-8} M_{\odot}$/year and for the mass of a black hole about $10 M_{\odot}$. In the Galaxy there must exist the point sources of hard γ-radiation with the luminosity $10^{34} \div 10^{37}$ erg/s.

Besides, bursts of soft γ-radiation are also possible. The stellar wind bears in itself a magnetic field frozen into plasma. The closed magnetic loops must be carried away into a black hole by an accreting flow.

The energy density of a magnetic field rapidly increases with the approach to a black hole. As well as on the sun, reconnection of magnetic field lines and the rapid and strong energy release, leading to the heating of accreting electrons up to relativistic temperatures $10^{11} \div 10^{13}$ °K, are possible under the certain conditions. The synchrotron radiation of relativistic electrons in magnetic field produces a great number of low-frequency (infra-red and optical) photons. These photons are subjected to multiple scatterings on relativistic electrons, increasing their own energy and the energy density of radiation. The parameter of comptonisation $u = 16\left(\frac{kT_e}{m_e c^2}\right)^2 \tau_T$ is great even though the optical depth τ_T of accreting gas for Thomson scattering is small.

When $u > 1$ the main part of energy is radiated in hard X-ray range ($h\nu \sim 50 \div 300$ keV). The flux of radiation with $h\nu \gtrsim 300$ keV [where $kT_e \cdot h\nu \gg (m_e c^2)^2$] is weaker because of the decreasing (in accordance with Klein-Nishina formula) of cross-section as well as of the value of frequency change during scattering. The resulting spectrum of radiation appears to be similar to the spectrum of observed cosmic γ-bursts. The sensitivity range of the UHURU counters permits to indicate only few percent of the total luminosity of γ-bursts. The total efficiency of accretion in this case depends on the distance of burst localization from the black hole and it may reach few percent during the burst. The corresponding luminosity makes up $10^{35} \div 10^{38}$ erg/s. The cause of bursts may be connected with the inhomogenity of a magnetic field in the stellar wind. The possibility of existence of quasi-stationary and rapidly fluctuating sources of hard X-ray radiation of such nature should be noted. For example an object, constituting the detached binary system X-Persei (Hutchings *et al.*, 1974), may appear to be the source of this kind. In this case, only a small part of its luminosity radiates in the band of 1–10 keV.

It follows from the results obtained by Illarionov and Sunyaev (1975a) that the view of sky in the hard X-ray and γ-ray bands may differ greatly from that observed by "UHURU".

c) Neutron Stars

It is only in case of an anomalously intensive stellar wind that a neutron star having strong magnetic field, may be an X-ray source. During a long period of life, the neutron star in a binary system is a pulsar emitting radio pulses and ejecting cosmic rays (Fig. 2a). However, it is difficult to observe the pulsar radioemission in close binaries because of the free-free absorption in a stellar wind plasma. In the course of time the luminosity of pulsar falls; the pressure of the ejected cosmic rays ceases to throw away the surrounding thermal plasma and it begins to penetrate under the light cylinder,

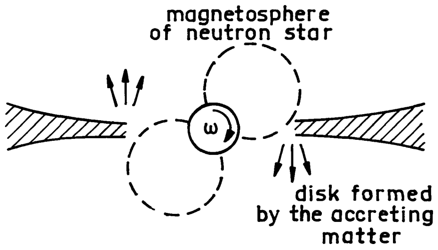

Fig. 3. Schematic picture, illustrating the interaction of "propeller" with accreting disk. Rotating magnetosphere destroys the disk and throws away the accreting matter from the neutron star

disturbing the normal operation of a pulsar mechanism (Schwartzman, 1971b).

The following more extended stage of neutron star life is characterized by the deceleration of its rotational velocity, which is too great for accretion (see point 1V B) to take place. Accretion of stellar wind matter onto the star surface is impossible and the neutron star is like a "propeller", throwing away the accreting gas by corotating magnetosphere (Figs. 3 and 2b). Only when rotation is slowed enough, the accretion onto the surface will be possible (Fig. 2c). For relatively small rate of accretion (because only small part of stellar wind matter is captured by gravitational field of neutron star), typical for a detached binary system, the deceleration time is too great and exceeds the evolutionary time of a normal component.

Consequently, neutron star may be a strong X-ray source only in the close binary system, where the intensive mass loss of a normal component filling its limiting Roche lobe takes place. In this case the deceleration time of neutron star is small compared to the evolutionary time of a normal component. This also accounts for the absence of a great number of weak X-ray sources in the Galaxy.

If the single neutron star possessing the magnetic field is in the interstellar medium, it cannot decelerate enough during the life of the Galaxy to allow interstellar matter to fall onto its surface. Therefore the old pulsars with strong magnetic field (even after the penetration of interstellar plasma under the light cylinder) never become weak soft X-ray sources accreting the interstellar matter. This conclusion follows from the assumption, that the magnetic field of the neutron stars does not dissipate with the time.

Useful Notations

$M = m M_\odot$	is a mass of normal star.
$M_r = m_r M_\odot$	is a mass of relativistic star.
$\dot{M} = \dot{m}\, 10^{18}$ g/s $= 1.5\; 10^{-8}\, \dot{m}\, M_\odot$/year	is a rate of matter loss from the normal star.
$\dot{\mathcal{M}} = \dot{\mu}\, 10^{15}$ g/s $= 1.5\; 10^{-11}\, \dot{\mu}\, M_\odot$/year	is a rate of matter accretion onto a relativistic star.
A	is a distance between the components of a binary system.
R_0	is a radius of a normal star.
$R_{cr} = 0.38 (m/m_r)^{0.208} A$	is the radius of critical Roche lobe of a normal star (supposed that $m > m_r$).
R	is a distance to a normal star.
r	is a distance to a relativistic star.
$r_g = 2GM/c^2$	is a gravitational radius of a black hole.
$a \simeq 10^6$ cm	is a radius of neutron star.
$r_A = \delta \dfrac{GM_r}{V_0^2} = 1.3 \cdot 10^{10}\, \delta\, m_r v_0^{-2}$ cm	is the capture radius of the stellar wind matter by relativistic star.
δ	is a dimensionless parameter of the order of unity.
$V_0 = v_0 \cdot 10^8$ cm/s	is a velocity of stellar wind.
$\alpha = V_0 \Big/ \left(\dfrac{2GM}{R_0}\right)^{\frac{1}{2}}$	is a dimensionless parameter of the order of unity, which characterises the mechanism of the mass loss from normal star.
$P = 2\pi \left(\dfrac{A^3}{G(M+M_r)}\right)^{\frac{1}{2}}$	is a period of a binary.
$p = 2\pi/\omega$	is a rotational period of neutron star.
$r_c = cp/2\pi$	is a radius of a light cylinder.
$H_0 = h \cdot 10^{11}$ Gauss	is a value of magnetic field at a surface of a neutron star.
$K \simeq \dfrac{H_0 a^3}{2} \simeq 10^{29} \cdot$ h gs $\cdot$ cm^3	is a magnetic moment of a neutron star.

II. Mass Accretion from a Stellar Wind

A) Stellar Wind Characteristics

Consider a spherically symmetric stellar wind which is formed by a matter outflowing from the surface of a normal star. The velocity of the flow far from the star is $V_0 = \text{const}$ (Fig. 1B). In accord with observations (Morton, 1967), the value of this velocity is of the order of 1000 km/s. On the other hand, it is close to a parabolic velocity $V_0 = \alpha\left(\frac{2GM}{R_0}\right)^{\frac{1}{2}}$. The value of parameter $\alpha \sim 1$ depends on the mechanism of the mass loss and is equal to $\alpha \simeq 2/3$ in the case of a solar wind and $\alpha \simeq 2$ for *O–B* stars of the main sequence (Morton, 1967).

The rate of mass-loss of normal stars varies in the range from $10^{-5} M_\odot\,\text{year}^{-1}$ for OB supergiants to $10^{-14} M_\odot\,\text{year}^{-1}$ for the Sun (Pottasch, 1970). The density of gas in stellar wind at a distance R from the star may be easily estimated: $\varrho = \dot{M}/4\pi R^2 V_0$ or $n = \dot{M}/4\pi R^2 V_0 m_p$.

B) Capture of the Stellar Wind Matter by the Relativistic Star

Consider a relativistic star (black hole or neutron star) of mass M_r at a distance A from a normal star. The particles of stellar wind follow the hyperbolic trajectories in a gravitational field of relativistic star encircling it. The particle density of the stellar wind is too low, that makes the situation collisionless. However, the intersection of flows is impossible because of the beaming instabilities [the instability increament under the conditions discussed is very great (Michailovskyi, 1970)] and because of the existence of magnetic field frozen into the gas. The collisionless shock wave is formed necessarily. The width of shock front is much smaller than both the accretion radius,

$$r_A = \delta \frac{GM_r}{V_0^2} = \frac{\delta}{2\alpha^2} \frac{m_r}{m} R_0 = 1.3 \cdot 10^{10} m_r \delta v_0^{-2}\ \text{cm} \quad (1)$$

and the dimensions of a binary system. The energy of plasma waves is turned quickly into the thermal energy.

Thus the part of kinetic energy of a gas $\left(\text{which is a sum of the initial kinetic } \frac{m_p V_0^2}{2} \text{ and the gravitational } \frac{m_p G M_r}{r} \text{ energies}\right)$ in the shock-wave is turned to the thermal energy. As a result the temperature of a gas is

$$T \simeq \frac{m_p V^2}{6k} = 4 \cdot 10^7 v_0^2 \frac{r_A}{r}\ ^\circ\text{K}. \quad (2)$$

The problem of the hydrodynamic accretion for great Mach numbers has not been solved. However one can assert the following:

1. The particles with the impact parameter $s < r_A$ lose energy in passing through the shock exceeding $\frac{m_p V_0^2}{2}$ (it is turned into heating) and fall inward upon the relativistic star. For $s > r_A$ kinetic energy of particles behind the shock is bigger than parabolic energy and particles are not captured by a relativistic star (Hoyle and Lyttleton, 1939; Zeldovich and Novikov, 1971).
2. For the accretion rate $\dot{\mu} \ll 10^3 m_r v_0$ the density of a captured matter is too small and the shock is emissionless. The accreting gas falls inward upon the relativistic star adiabatically, because the cooling time of the gas due to bremsstrahlung $t_{ff} = \frac{3nkT}{W_{ff}} = 3 \cdot 10^{11}\, T^{1/2} n^{-1}$ s exceeds the free-fall time $t = r^{3/2}/(2GM_r)^{\frac{1}{2}}$ for every $r < r_A$.
3. The accreting gas falls toward the relativistic star within a great solid angle. Firstly, the adiabatic index of the emissionless gas is close to $\gamma = 5/3$. Therefore the density just behind the shock is $\varrho_2 = \frac{\gamma+1}{\gamma-1} = 4\varrho_1$, where ϱ_1—the density of gas before the shock. Secondly, the condition of equality of mass inflowing through the lateral surface of the shock cone $\varrho_1 \cdot 2\pi r z V_0 = \varrho_1 \cdot 2\pi r^2 V_0 \sin\beta$ and of mass outflowing through the cross-section surface $\varrho_2 \cdot \pi z^2 V_0 = \varrho_2 \pi r^2 V_0 \sin^2\beta$ results in $\varrho_2 = \frac{2}{\sin\beta} \varrho_1$. It is easy to find that $\sin\beta \simeq \frac{1}{2}$, and apex angle of cone is $\beta \simeq 1$.
4. Moreover, in the conditions under discussion the accretion apparently becomes close to spherical-symmetric one (Hunt, 1971; Schwartzman, 1971a). Adduce the arguments in favour of this conclusion. Were the matter accreting within a cone with a constant apex angle β, the pressure of a flow would increase as $nkT \simeq \varrho v^2 \sim r^{-5/2}$, because $\varrho \sim r^{-3/2}$ and $v \sim r^{-1/2}$. On the other hand, it is known (Danby and Camm, 1957) that the pressure on a shock-wave front ϱv^2 is proportional to $r^{-3/2}$ with $\varrho \sim r^{-1/2}$ and $v \sim r^{-1/2}$. It follows, that angle β has to increase with radius decreasing, while the accreting flow has to take the spherically-symmetric form. At the distance of the order of r_A in front of the relativistic star the bow shock has to be formed (Fig. 1). This assumption is confirmed by numerical computations (Hunt, 1971). However these numerical results were obtained only for small Mach numbers ($M < 2.4$). In the considered case Mach numbers are very great.
5. In case of extremely intensive stellar wind accretion, for $\dot{\mu} > 1000 m_r v_0$, the matter after the shock has enough time to cool down due to free-free radiation. The matter falls inward upon the relativistic star and forms a dense stream with temperature $T \simeq 10^4 \div 10^5\ ^\circ$K. In this

paper we shall restrict our consideration to the case when $\dot{\mu} < 1000\, m_r v_0$ and the fall of accreting gas is emissionless.

C) Fraction of Mass Inflow Captured by the Compact Star

Knowing the accretion radius r_A and the orbit size A it is easy to show that in detached binary systems the accretion rate $\dot{\mathscr{M}}$ is much smaller than the rate of the mass loss by a normal star $\dot{M}$ (Shakura and Sunyaev, 1973)

$$\frac{\dot{\mathscr{M}}}{\dot{M}} = \frac{\pi r_A^2}{4\pi A^2} = 5 \cdot 10^{-4} \frac{\delta^2}{v_0^4} \frac{m_r^2}{(m+m_r)^{2/3}} \left(\frac{P}{1\ \text{day}}\right)^{-4/3}$$
$$= 10^{-2} \left(\frac{\delta}{\alpha^2}\right)^2 \left(\frac{m_r}{m}\right)^{1.6} \left(\frac{R_0}{R_{cr}}\right)^2 . \qquad (3)$$

Here $\frac{R_0}{R_{cr}}$ is the degree of filling of the critical Roche lobe by a normal star.

D) Angular momentum of the Captured Matter

Consider the relativistic object in the flow of stellar wind matter. In the case of an axisymmetric homogeneous flow of the gas, the resulting angular momentum of the matter captured by a relativistic star is identically equal to zero. However the problem under consideration is axisymmetric only in the zero approximation. The sources of nonzero angular momentum of captured matter are the following:

1) the orbital motion $\left(\text{with angular velocity } \Omega = \frac{2\pi}{P}\right)$ of the relativistic star in a binary system,
2) the rotation of a normal star,
3) the spatial inhomogeneities of density and velocity of the stellar wind matter. We shall dwell on the first two points.

1. The matter flow, captured by the relativistic star may be considered as the cylinders with the radius r_A. On average the matter velocity in this cylinder are equal to $\boldsymbol{V} = \boldsymbol{V}_0 + [\boldsymbol{\Omega} \boldsymbol{A}]$. The presence of the tangential velocity is equivalent to the rotation of the cylinder axis (and the axis of the shock-wave cone) by a small angle $\varphi = \operatorname{arctg} \frac{|[\boldsymbol{\Omega} \boldsymbol{A}]|}{V_0} = \frac{\Omega A}{V_0}$, e.i. in the first approximation the picture remains axisymmetric. It is obvious that in this approximation the total angular momentum of the captured matter is equal to zero as before.

Consider the thin disk which is the cylinder cross-section. The velocities of different particles in this disk differ due to the orbital motion by the value $\Delta \boldsymbol{V} = [\Omega \boldsymbol{s}]$, where $\boldsymbol{s}$ is the particle impact parameter. Therefore the specific angular momentum of the accreting matter is approximately equal to the specific angular momentum of the homogeneous disk rotating around its diameter with angular velocity Ω.

$$Q = \tfrac{1}{4} \Omega r_A^2 . \qquad (4)$$

The exact solution of a hydrodynamic accretion problem in a binary system, which takes into account the distortion of the form of cylinder, the departure from the homogeneity of the flow and etc., may augment the dimensionless factor to the Eq. (4)[1]). Below we shall suppose that $Q = \frac{1}{4} \Omega r_A^2$. Note that this value is much smaller $\left(\text{in } \frac{\dot{\mathscr{M}}}{\dot{M}} \text{ times, see Eq. (3)}\right)$ than the specific angular momentum of the binary system ΩA^2.

2. The rotation of normal star at $R_0 \ll A$ makes only a negligible contribution to the total angular momentum of the accreting matter. Really, the rotational velocity of the stellar surface is less than parabolic velocity $\Omega_0 R_0 < (2GM/R_0)^{1/2}$. The angular velocity of the stellar wind matter decreases with a distance to the star $\Omega_w = \Omega_0 \left(\frac{R_0}{R}\right)^2$ in accordance with the law of conservation of angular momentum. It is easy to see that

$$\Omega_w(A) = \Omega_0 \left(\frac{R_0}{A}\right)^2 < \left(\frac{2GM}{R_0^3}\right)^{1/2} \left(\frac{R_0}{A}\right)^2$$
$$\simeq \Omega \left(\frac{R_0}{A}\right)^{1/2} < \Omega .$$

And accordingly, a contribution of a stellar rotation to a total specific angular momentum of the captured matter is small

$$\Delta Q \simeq \Omega_w(A)\, r_A^2 \ll Q .$$

3. The spatial inhomogeneities in the stellar wind flow reduce the effective radius of accretion and may lead to the nonstationarity of accretion. This is an additional source of rapid fluctuations of X-ray radiation of black holes in binaries (Illarionov and Sunyaev, 1975b).

III. Condition for Realization of the Disk Accretion

If angular momentum of the matter accreting into a black hole is great, disk orbiting around black hole will be formed. The viscosity, connected with the turbulent motions and the magnetic fields, enables angular momentum to be transferred outward. In so doing the particles in the disk spiral into the black hole. Gravitational energy is released during this spiraling. According to the models of disk accretion onto a black hole (Shakura, 1972; Pringle and Rees, 1972; Shakura and Sunyaev, 1973), the main part of energy is released at $r \sim 1 \div 10 r_g$ and is emitted in X-ray spectral band.

[1]) The turn of the shock-wave with respect to the binary system axis may bring about additional compensation of particle velocities and the reduction of the specific angular momentum of a captured matter.

In the case of Schwarzschild black hole, the particles on the last inner stable orbit with $r = 3r_g$ have a specific angular momentum equal to $Q_{\min} = \sqrt{3}\, r_g c$ [2]. The condition of disk formation is obvious: a specific angular momentum of accreting matter must exceed $Q_{\min}$, i.e.

$$\tfrac{1}{4}\Omega r_A^2 > \sqrt{3}\, r_g c\,. \tag{5}$$

This condition takes place when the period of binary system $P < 0.2\, m_r v_0^{-4}\, \delta^2$ day, or when a normal star fills the essential part of the limiting Roche lobe

$$\frac{R_0}{R_{cr}} \geqq 0.5\left(\frac{\alpha^2}{\delta}\right)^{4/3}\left(\frac{m}{m_r}\right)^{0.46}\left(1+\frac{m_r}{m}\right)^{-1/3}\left(\frac{mR_\odot}{R_0}\right)^{1/3}$$
$$\simeq 1.8\left(\frac{v_0^2}{\delta}\right)^{4/3}\left(\frac{m}{m_r}\right)^{0.46}\left(1+\frac{m_r}{m}\right)^{-1/3}\left(\frac{R_0}{mR_\odot}\right), \tag{6}$$

where $R_\odot = 7\cdot 10^{10}$ cm is the radius of the Sun. It is only in the close binaries that disk accretion may take place, where matter flows mainly through the inner Lagrangian point with a small velocity $V \ll V_{\rm orb}$ and the captured matter have a great specific angular momentum.

IV. Neutron Star in a Binary System

It is likely that neutron stars originate with a small period of rotation $p \ll 1$ s and with a strong magnetic field $H_0 \gg 10^9$ Gauss. It means that at the early stage of their life, they are radiopulsars and they also intensively emit X-rays like the pulsar in Crab nebula. What is the further destiny of a pulsar in a binary system?

A) Suppression of the Pulsar Emission by the Stellar Wind

Joung pulsar loses its rotation energy for radiation and acceleration of cosmic rays. Schwartzman (1971b) noted, that when the pulsar period becomes bigger than a certain critical p_{cr}, neither magnetic field nor magnetic dipole radiation and cosmic rays ejected by a pulsar, can prevent the penetration of accreting gas into a light cylinder. It leads to the suppression of pulsar ejection of cosmic rays and of mechanism of pulsar radiation.

a) Strong Stellar Wind

Evaluate the value of p_{cr}. The total luminosity of a pulsar with a given period $p = \frac{2\pi}{\omega}$ is equal to

$$L = \frac{2}{3}\,\frac{K^2\omega^4}{c^3} = 4\cdot 10^{29}\, h^2 p^{-4}\,{\rm erg\,s^{-1}}, \tag{7}$$

[2]) In extreme Kerr metric $Q_{\min} = \frac{1}{\sqrt{3}} r_g c$ for parallel rotational axes of the binary system and of the black hole itself. In the opposite case of antiparallel axes $Q_{\min} = \frac{11}{3\sqrt{3}} r_g c$ (Zeldovich and Novikov, 1971). For estimations we shall make use of $Q_{\min} = \sqrt{3}\, r_g c$.

where $K \simeq \frac{H_0 a^3}{2} \simeq 10^{29} h$ Gauss cm^3 is a magnetic moment of a neutron star, $H_0 = h\cdot 10^{11}$ Gauss is the value of magnetic field on its surface. This value of -luminosity includes ejection of cosmic rays, carring away also the magnetic field of a neutron star (Goldreich and Julian, 1969). A pulsar acts normally till at the radius of capture r_A the pressure of the cosmic rays and of the magnetic field $(L/4\pi r_A^2 c)$ exceeds the pressure of stellar wind gas ϱV_0^2 and of the matter behind the shockwave, i.e. till

$$L > 4\pi r_A^2 c\,\varrho\, V_0^2 = 4\dot{\mathcal{M}}\, V_0\, c \tag{8}$$

this corresponds to the value of pulsar period

$$p < p_{cr} = \frac{2\pi}{c}\left(\frac{K^2}{6\dot{\mathcal{M}}\, V_0}\right)^{1/4}$$
$$= 7.5\cdot 10^{-2}\, h^{1/2}\, v_0^{-1/4}\, \dot{\mu}^{-1/4}\ {\rm s}\,. \tag{9}$$

With the radius decreasing $(r < r_A)$ the pressure of the accreting flow $\varrho v^2 \sim r^{-5/2}$ grows quicker than the pressure of the cosmic rays and of magnetic field of the pulsar. When the pulsar period becomes bigger than p_{cr}, it is impossible to keep the accreting plasma at the distance r_A from a neutron star. The matter fall begins and it penetrates into the light cylinder $r_c = \frac{cp}{2\pi}$ inhibiting the further pulsar operation. The accreting gas flow may be stopped only inside the light cylinder by the rapidly growing $\left(\frac{H^2}{8\pi} \sim r^{-6}\right)$ pressure of the magnetic field of a neutron star. Equating the magnetic field pressure to the pressure of accreting flow

$$\left.\frac{H^2}{8\pi}\right|_{r_H} = \left.\varrho v^2\right|_{r_H} = \frac{\dot{\mathcal{M}}}{4\pi r_H^2}\left(\frac{2GM_r}{r_H}\right)^{1/2}$$

we may find the radius of magnetosphere where the accreting matter stops (Pringle and Rees, 1972; Lamb *et al.*, 1973; Davidson and Ostriker, 1973)

$$r_H = \left(\frac{2K^4}{\dot{\mathcal{M}}^2 G M_r}\right)^{1/7} = 4\cdot 10^8\, h^{4/7}\, \dot{\mu}^{-2/7}\, m_r^{-1/7}\ {\rm cm}\,.$$

In accordance to (7), the pulsar deceleration down to p_{cr} takes the following time

$$t(p_{cr}) = \frac{I\left(\frac{2\pi}{p_{cr}}\right)^2}{2L(p_{cr})} = \frac{3c^3 I}{4K^2}\left(\frac{p_{cr}}{2\pi}\right)^2 = \frac{3cI}{4K\sqrt{6\dot{\mathcal{M}}\, V_0}} \tag{11}$$
$$= 10^7\, h^{-1}\, \dot{\mu}^{-1/2}\, v_0^{-1/2}\, m_r\ {\rm year}$$

where $I \simeq 10^{45}\, m_r$ g$\cdot$cm^2-moment of inertia of a neutron star [3]. This is the life time of ejecting pulsar in a binary system (Schwartzman, 1971b).

[3]) The parameters of neutron star were taken from the paper of Cohen and Cameron (1971).

b) Weak Stellar Wind

When stellar wind is weak, the situation is possible when the pulsar is ejecting and the radius of its light cylinder $r_c = \frac{cp}{2\pi} > r_A$. This takes place for $p > 2.6 m_r \cdot v_0^{-2}$ s. In this case the life time of pulsar

$$t(p_{cr}) = \frac{3cI}{4K}\left(\frac{r_A^2}{6\dot{\mathcal{M}} V_0 K}\right)^{1/3} = 10^{10} h^{-4/3} v_0^{-5/3} \dot{\mu}^{-1/3} m_r^{5/3} \text{ yrs}$$

and the critical period

$$p_{cr} = \frac{2\pi}{c}\left(\frac{r_A^2 K^2}{6\dot{\mathcal{M}} V_0}\right)^{1/6} = 0.25 h^{1/3} v_0^{-5/6} \dot{\mu}^{-1/6} m_r^{1/3} \text{ s}$$

may be found from equality $\frac{L}{4\pi r_c^2 c} = \varrho V_0^2 = \frac{\dot{\mathcal{M}} V_0}{\pi r_A^2}$.
When $t > t(p_{cr})$, the stellar wind plasma penetrates into a light-cylinder. However, the accretion is not possible as $r_H > r_A$ (it is obvious that $r_H \simeq r_c$ for $p \simeq p_{cr}$). The stellar wind flows around the rotating dipole, graviational influence of a neutron star on the wind is small. This situation is similar to the case of solar wind flowing around the magnetosphere of the Earth.
Providing $r_H > r_A$ it is easy to find the criterion of the stellar wind weakness

$$\dot{\mathcal{M}} < \frac{K^2 V_0^7}{(GM_r)^4}, \quad \dot{\mu} < 10^{-5} h^2 v_0^7 m_r^{-4}.$$

However, these formulae are extremely rough because the dependence on parameters is rather strong. Below the formulae will be given only for the case of a strong stellar wind.

B. The Further Increase of the Period. Neutron Star as a "Propeller"

For $p > p_{cr}$ the accreting gas penetrates into the light cylinder, but it can not reach the surface of a neutron star. The case is that the neutron star has a powerful magnetosphere, corotating with a neutron star. The velocity of this rotation near the light cylinder is great $\simeq c$ and considerably exceeds the parabolic velocity at the distance $r_H \simeq r_c$.

a) Asymmetry of Magnetic Field of a Neutron Star and the "Propeller"

It is obvious that the magnetosphere is not axisymmetric. Thus for example the square of the dipole magnetic field strength at a given radius $r = \text{const}$ depends on the direction $H^2(\theta) = H^2(0)\frac{1+3\cos^2\theta}{4}$ where θ is an angle between this direction and the dipole axis. The surface of $\frac{H^2}{8\pi} = \text{const}$ is not a sphere[4]). Consider as an example the section of a dipole by a plane crossing it in the centre and inclined to its axis at an angle of 45°. In this case the line with $\frac{H^2}{8\pi} = \text{const}$ is an ellipse with a big axis exceeding the small one by 17%. On a circle with the radius r, the value of the field pressure $\frac{H^2}{8\pi}$ changes by 2.5 times.
If the axes of rotation and of a magnetic dipole do not coinside, the value $\frac{H^2}{8\pi}$ considerably and periodically changes in every point of the space. The magnetic dipole (undoubtedly distorted by the interaction with the accreting matter) represents a "propeller", rotating with a supersonic velocity in the accreting gas. It throws away the infalling matter, preventing it from falling onto the surface of a neutron star.
Since the rotation velocity of the "propeller" is supersonic, it generates shock-waves intensively heating the accreting matter and leading to its hydrodynamic outflow. It is difficult to imagine the exact picture of the fall and outflow of the accreting gas. It is only obvious that in case of strong dissipation of shock-wave energy, the velocity of sound in the accreting matter at a distance r_H (close to the parabolic velocity[5]) at this radius) is the characteristic velocity of the problem. Below, carrying out evaluations, we shall assume that the accreting matter is flung away with the velocity $v \simeq (2GM_r/r_H)^{1/2}$.

b) Conditions of Accretion onto the Surface of Neutron Star

The deceleration of rotation of a neutron star obeys the equation

$$I\omega\frac{d\omega}{dt} = -\dot{\mathcal{M}}\frac{GM_r}{r_H}, \qquad p = \frac{2\pi}{\omega} = p_{cr}\Big/\left(1 - \frac{t}{t_A}\right)^{1/2} \tag{12}$$

till $r_H < r_{eq}$. For $r = r_{eq} = \left(\frac{GM_r}{\omega^2}\right)^{1/3}$ the rotational velocity of the magnetic dipole becomes equal to Keplerian one. If $r_H \simeq r_{eq}$, the dipole rotation does not lead to the outflow of gas and can not prevent the accretion onto the surface of neutron star. Thus the

[4]) The numerical computations of the dipole field deformation in a steady-state plasma have shown that the surface of the constant pressure of a magnetic field is also not spherical (Slutz, 1962).
[5]) The other characteristic velocity is the rotational velocity of magnetosphere at a distance r_H. It is much bigger than the velocity of sound.

accretion onto the surface of the rotating neutron star is possible only for $p \gtrsim p_{eq}$, where

$$p_{eq} = 2\pi r_H^{3/2} (G M_r)^{-1/2} = 4 h^{6/7} \dot{\mu}^{-3/7} m_r^{-5/7} \text{ s} \quad (13)$$

is found from the condition that $r_H = r_{eq}$ (Pringle and Rees, 1972; Davidson and Ostriker, 1973; Lamb *et al.*, 1973).

The deceleration time of the neutron star till the beginning of accretion onto its surface can be easily found from (12)

$$t_A = \frac{2\pi^2 I r_H}{\dot{\mathcal{M}} G M_r p_{cr}^2} = \frac{4 r_H c V_0}{G M_r} t(p_{cr}) \quad (14)$$
$$= 4 \cdot 10^8 h^{-3/7} \dot{\mu}^{-11/14} v_0^{1/2} m_r^{-1/7} \text{ yrs}.$$

This time does not practically depend on p_{eq}. The power of the new born X-ray source will be close to $L_x \simeq 10^{35} \dot{\mu} m_r$ erg s^{-1}.

C. Discussion

The lifetime of a star on the main sequence may be evaluated from the approximate formula $t_{ev} = 10^{10} \cdot m^{-3}$ yrs (Martynov, 1971). Comparing this time with the characteristic time of a neutron star deceleration t_A (14), we see that $t_A > t_{ev}$ for all the stars with

$$m > 3 h^{1/7} \dot{\mu}^{11/42} v_0^{-1/6} m_r^{1/21} \quad (15)$$

or, what is analogous, with

$$m > 3.3 h^{0.1} \dot{m}^{0.185} v_0^{-0.12} m_r^{0.3} \alpha^{-0.75} \left(\frac{R_0}{R_{cr}}\right)^{0.37}. \quad (15a)$$

These estimates are obtained under the assumption that the rate of the mass loss by a normal star is constant. The stars of the main sequence with the small mass $m < 3$ lose mass extremely weakly. While examining them, we should use the formulae, obtained for the weak stellar wind [see Section Ab].

It is obvious, that in the case of weak stellar wind the accretion is impossible at any age of the neutron star.

In case of massive stars, it is seen from (15) that the normal star leaves the main sequence before the neutron star decelerates and acretion begins.

Thus for example, the evolution of OB stars ($m > 8$) losing in accordance with Morton (1967) the mass with an enormous rate $\dot{m} \simeq 100$ for $\alpha \simeq 2$ goes much faster than the deceleration of a neutron star.

One then concludes: if the dimensions of a normal star are smaller than the critical Roche lobe and the outflow has the character of the stellar wind, then the accretion onto the surface of a neutron star in a binary system is hardly ever possible. This is one of the reasons of the fact that there are so few galactic X-ray sources. At the same time, the conditions may be indicated, when the accretion becomes possible. If the stellar wind was weak at the begining, the ejecting pulsar acts for a long time, the rotation period of a neutron star becomes great. The leaving by a normal star of the main sequence, may lead to the intensification of the stellar wind. Since the rotational period is rather long, we have the conditions for accretion and the X-ray source appears.

In the next section it will be shown that when the star fills its Roche lobe and the outflowing matter forms disk around the neutron star, the conditions favourable for accretion are realized as well.

a) Disk Accretion Onto a Neutron Star

In the extremely close binaries, when the dimensions of a normal star are close to the critical Roche lobe, the disk is formed around a neutron star. It is easier for the matter forming a thin disk penetrate to a light cylinder, that is why in this case the lifetime of a pulsar is shorter than in the case of the stellar wind.

The deceleration time of a neutron star till the begining of accretion also diminishes. Really, the matter forms a thin disk (Fig. 3). The vanes of a "propeller" strike the disk at a certain angle and may throw the matter away into a zone free from gas. Therefore the velocity of the outflowing matter may considerably exceed the parabolic one in the region of the interaction of the disk with the rotating magnetosphere $\left(\frac{2GM_r}{r_H}\right)^{1/2} < v < \omega r_H$.

The rate of rotational energy losses by a neutron star increases correspondingly and the time of its deceleration decreases.

The accretion becomes possible when the radius of the disk destruction by the magnetic field is close to $r_{eq} = \left(\frac{G M_r p^2}{4\pi^2}\right)^{1/3}$. It should be recalled that near r_{eq} the rotation velocity of the magnetosphere ωr is equal to the Keplerian velocity of matter in the disk. It follows from (13) that the period of accreting pulsars P_{eg} depends on h and $\dot{\mathcal{M}}$ and may exceed 10 sec.

The rotational period of a neutron star $p \simeq p_{eq}$ in the course of accretion may be subject to small deviations in different directions. This is connected with a partial compensation of two factors: the acceleration of rotation due to the angular momentum of the accreting matter captured from the rapidly rotating disk (Pringle and Rees, 1972) and the deceleration of rotation due to the angular momentum transport outward by the matter of accreting disk.

The considerable diminition of $\dot{\mu}$ may lead to the exceeding of the destruction radius of the disk in comparison with r_{eq} and to the switch off of the accretion. It seems that this may be possible cause of the observed switching off of the optical variability of HZ Her (Wentzel and Gessner, 1972; Jones *et al.*, 1973), reflecting the fact of X-ray source Her X1 switching off.

b) Radiopulsars in Binary Systems

Till the recent discovery of the radiopulsar in binary system, the question was often discussed: "Why the radiopulsars in binary system are not observed?"

This problem was discussed in a number of papers (see for example Gunn and Ostriker, 1970; Schwartzman, 1971b; Bisnovatyi-Kogan and Komberg, 1974) in most of which the absence of radiopulsars in binary systems was explained by the disruption of pair due to supernova explosion or by the dissipation of magnetic field of neutron stars. The existence of X-ray sources and the radiopulsar in binary proved that not all the pairs are destroyed during the supernova explosion and that the neutron stars having the strong magnetic field should be present in binary systems. The estimates of the previous section (see also Schwartzman, 1971b) show that the lifetime of radiopulsars in binaries is rather great.

It should be noted that the pulsar radioemission must be absorbed even by the plasma of the weak stellar wind. The optical depth of stellar wind for free-free absorption [6])

$$\tau_{ff} = 2\cdot 10^{-23} n^2 T^{-3/2} \lambda^2 g A$$

$$= 250\dot{m}^2 \left(\frac{10^{13}\,\mathrm{cm}}{A}\right)^3 \left(\frac{\lambda}{75\,\mathrm{cm}}\right)^2 \left(\frac{T}{10^4\,{}^\circ\mathrm{K}}\right)^{-3/2} \quad (16)$$

$$= 100\dot{m}^2 (m+m_r)^{-1} \left(\frac{\lambda}{75\,\mathrm{cm}}\right)^2 \left(\frac{T}{10^4\,{}^\circ\mathrm{K}}\right)^{-3/2} \left(\frac{P}{1\,\mathrm{yr}}\right)^{-2}$$

is great in a longwavelength spectral band ($\lambda \sim 75$ cm) where the search for radiopulsars is carried out. Note that the temperature of stellar wind plasma must be much less than $\frac{m_p V_0^2}{6k}$ and be close to $10^4 \div 10^5$ °K.

Apparently the number of radiopulsars in binary systems may be great. However it is rather difficult to observe them, because the longwave radioemission is absorbed by stellar wind plasma, while the shortwave radioemission intensity of the pulsars is usually small by itself. Radiopulsars may be observed only in the strongly separated binaries or in the binaries, where both stars are dead. This may be pairs of neutron star with white dwarf, another neutron star or black hole (see, also Bisnovatyi-Kogan and Komberg, 1974).

Recall that the young ejecting pulsars in binaries may be strong X-ray sources like Crab and Vela pulsars, which are single. The luminosity of such pulsars may appreciably exceed the Eddington critical luminosity 10^{38} erg/s, i.e. there is an opportunity to observe them in another galaxies. It is possible that Cyg X3 represents a case of a young pulsar in binary system, beam of which never covers the Earth. We observe in this case only the X-rays and infrared radiation reflected by the stellar wind and the surface of normal star. The radioemission of pulsar itself is absorbed by stellar wind. The radioflares are a consequence of ejection of the cosmic rays during neutron star quakes (Basko *et al.*, 1974).

[6]) Here g is Gaunt-factor, n and T are density and temperature of electrons in stellar wind plasma.

c) Single Neutron Star

What is the fate of the single "old" radiopulsar possessing strong magnetic field? Schwartzman (1970), Ostriker *et al.* (1970) suppose that in the course of time interstellar matter begins to accrete onto "old" pulsar, which turns into weak ultraviolet or soft X-ray source. The formulae received earlier show that the accretion does not go on the "old" single pulsar. The time of its deceleration exceeds the age of the Galaxy.

Suppose the "old" pulsar moves with velocity $u \sim 10 \div 100\,\mathrm{km\,s^{-1}}$ through the interstellar medium. The possible rate of accretion is very small

$$\dot{\mathcal{M}} = \pi n m_p u \left(\frac{G M_r}{u^2}\right)^2,$$

$$\dot{\mu} = 10^{-4} m_r^2 \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right) \left(\frac{u}{10\,\mathrm{km/s}}\right)^{-3}.$$

The radiopulsar mechanism is suppressed during the time

$$t(p_{cr}) = \frac{3cIu}{4KGM_r}(6\pi m_p n)^{-1/2}$$

$$\simeq 10^{10} h^{-1} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \left(\frac{u}{10\,\mathrm{km/s}}\right) \mathrm{yrs} \quad (17)$$

when its period is

$$p_{cr} = \frac{2\pi}{c}\left[\frac{K^2 u^2}{6\pi m_p n G^2 M_r^2}\right]^{1/4}$$

$$= 2.5 h^{1/2} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/4} \left(\frac{u^2}{10\,\mathrm{km/s}}\right)^{1/2} m_r^{-1/2}\,\mathrm{s}. \quad (18)$$

This is maximal possible period for a single radiopulsar.

After this the neutron star acts as a "propeller". The accretion of interstellar gas onto a surface of neutron star is possible only in the time

$$t_A = \frac{2\pi^2 I r_H}{\mathcal{M} G M_r p_{cr}^2}$$

$$= 5\cdot 10^{10} h^{-3/7} m_r^{-12/7} \cdot \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-11/14} \left(\frac{u}{10\,\mathrm{km/s}}\right)^{20/7} \mathrm{yrs} \quad (19)$$

exceeding in wide range values of parameters the age of the Galaxy. The old pulsar possessing the magnetic field can never become the accreting sourse of hard radiation and only dissipation of magnetic field can promote the accretion.

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