Neutrinos from accreting milisecond pulsars

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Abstract. **Milisecond pulsars inside the binary systems can accrete the matter which reach the neutron star surface provided that its period is not very short. In order to accreate onto the surface, the matter has to be accelerated to the rotational velocity of the pulsar at the Alfven distance R_A. A very turbulent, magnetized region is created at R_A in which hadrons can be accelerated to relativistic energies. These hadrons can interact at first with the radiation of the hot spot on the NS surface (created by the accreting matter) and next with the matter of the accretion column over the magnetic pole. We calculate the expected spectra and fluxes of neutrinos produced in such scenario and discuss their possible observability by the IceCube scale detector.**

***Keywords*: Neutrinos - stars: binaries - neutron stars**

I. Introduction

A large number of neutron stars (NS) has been discovered as close companions of low mass and high mass stars (so called low mass and high mass X-ray binaries, see [1], [2]). These binaries are characterized by a strong X-ray emission that is produced as a result of matter accretion from the companion star onto the neutron star. In some cases, the matter arrives up to the NS surface at the magnetic polar cap region which creates a very hot spot (so called X-ray pulsars, see [3]). Here we consider the millisecond pulsars (MSPs) that are mostly contained within globular clusters [4]. According to the standard scenario, the MSPs are old pulsars spinned up by the angular momentum transfered to the NS from the accreting matter.

The matter that is falling onto the NS as a result of the overflow through the inner Lagrangian point usually contains a large angular momentum. This matter forms an accretion disk that can be disrupted at the inner radius due to the pressure of the magnetic field of the NS. In the case of accretion from the wind of the massive star, the process occurs more spherically due to the isotropization of the accretion flow by the shock in the massive star wind. Accreting pulsars can suffer spin up and spin down periods depending on the conditions inside the binary system and the parameters of the MSP (i.e. the mass loss rate of the companion star, distance between the stars, neutron star velocity, surface magnetic field strength and the MSP rotational period). These basic parameters determine the specific accretion phase of the matter onto the NS, i.e. whether it is in the accretor, the propeller, or the ejector phase. The ejector phase is characteristic for a fast rotating NS whose magnetized wind is able to prevent any accretion below the light cylinder radius. In the propeller phase, matter can enter the inner pulsar magnetosphere. However, it is blocked by the NS fast rotating magnetosphere at a certain distance from the NS surface due to the centrifugal force. Then, most of the matter is expelled from the vicinity of the pulsar and the accretion onto the neutron star surface may occur only episodically when the pressure of the accumulated matter overcomes the pressure of the rotating magnetosphere.

In this paper we assume that hadrons can be efficiently accelerated at the transition region where the pressure of accreting matter is balanced by the magnetic pressure of rotating magnetosphere. We estimate the neutrino fluxes produced by such hadrons in such a model.

II. Pulsar inside binary system

In this paper we are interested in the accretion process onto the NS surface occurring in the accretor phase. In this phase the matter passes through the inner pulsar magnetosphere onto the surface of the neutron star. It is characteristic for NSs which are relatively slow rotators with a weak surface magnetic field. The gravitational energy of the accreting matter is released on the neutron star surface, producing a hot spot around the magnetic pole. The amount of released energy is re-emitted as thermal X-ray emission whose the power can be estimated from:

$$L_{\rm X} = \frac{G\dot{M}_{\rm acc}M_{\rm NS}}{R_{\rm NS}} \approx 2\times 10^{36}M_{16}\quad {\rm erg~s^{-1}}, \qquad (1)$$

where $\dot{M}_{\rm acc} = 10^{16}M_{16}$ g s^{-1} is the accretion rate, and $L_{\rm X}$ is the X-ray thermal emission from the polar cap region. The radius and the mass of the NS is assumed to be $R_{\rm NS} = 10^6$ cm and $M_{\rm NS} = 1.4M_\odot$.

The distance from the NS surface at which the magnetic field starts to dominate the dynamics of the in-falling matter (the Alfven radius) can be estimated by comparing the magnetic field energy density to the kinetic energy density of the wind, $B_{\rm A}^2/8\pi = \rho v_{\rm f}^2/2$, where $B_{\rm A}$ is the magnetic field in the inner neutron star magnetosphere, $\rho = \dot{M}_{\rm acc}/(\pi R_{\rm A}^2 v_{\rm f})$ is the density of the accreting matter, $v_{\rm f} = (2GM_{\rm NS}/R_{\rm A})^{1/2}$ is the free fall velocity of the accreting matter, $R_{\rm A}$ is the Alfven radius, and G is the gravitational constant.

By applying Eq. 1, and assuming that the magnetic field in the neutron star magnetosphere is of the dipole type, i.e. $B_{\rm A} = B_{\rm NS}(R_{\rm NS}/R_{\rm A})^3$, we estimate the location of $R_{\rm A}$ with respect to the NS surface:

$$R_{\rm A} = 7.8 \times 10^6 B_9^{4/7} M_{16}^{-2/7} \quad {\rm cm}, \tag{2}$$

where the magnetic field at the neutron star surface is $B_{\rm NS} = 10^9 B_9$ G.

Then, we can estimate the magnetic field strength at the transition region,

$$B_{\rm A} = 3.3 \times 10^6 M_{16}^{6/7} B_9^{-5/7} \quad {\rm G}. \tag{3}$$

The observed thermal luminosity in X-rays, re-radiated from the region of the polar cap, can be calculated from $L_{\rm X} = \pi R_{\rm cap}^2 \sigma T_{\rm cap}^4$, where σ is the Stefan-Boltzman constant. The radius of the polar cap region on the NS surface, onto which the matter falls, and from which thermal X-ray radiation is emitted, can be estimated from (assuming a dipole structure of the magnetic field):

$$R_{\rm cap} = (\frac{R_{\rm NS}^3}{R_{\rm A}})^{1/2} \approx 3.6 \times 10^5 B_9^{-2/7} M_{16}^{1/7} \quad {\rm cm}. \tag{4}$$

Then, the surface temperature of the polar cap has to be,

$$T_{\rm cap} = (\frac{L_{\rm X}}{\pi R_{\rm cap}^2 \sigma})^{1/4} \approx 1.8 \times 10^7 B_9^{1/7} M_{16}^{5/28} \quad {\rm K}. \tag{5}$$

In general, the accretion of matter onto the NS can occur provided that the radius of the transition region (i.e. the Alfven radius $R_{\rm A}$) lies inside the light cylinder radius of the neutron star, i.e $R_{\rm A} < R_{\rm LC} = cP/2\pi$, where P is the rotational period of the neutron star in seconds , and c is the velocity of light. This condition is fulfilled for,

$$P > P_{\rm p} = 1.7 \times 10^{-3} B_9^{4/7} M_{16}^{-2/7}. \tag{6}$$

Moreover, the rotational velocity of the magnetosphere at $R_{\rm A}$ has to be larger than the keplerian velocity of the accreting matter. If the rotational velocity, given by

$$v_{\rm rot} = \frac{2\pi R_{\rm A}}{P} \approx 4.8 \times 10^7 B_9^{4/7} M_{16}^{-2/7}/P \quad \frac{\rm cm}{\rm s}, \tag{7}$$

is larger than the keplerian velocity,

$$v_{\rm kep} = (\frac{G M_{\rm NS}}{R_{\rm A}})^{1/2} \approx 4.8 \times 10^9 B_9^{-2/7} M_{16}^{1/7} \quad \frac{\rm cm}{\rm s}, \tag{8}$$

then the matter cannot accrete directly onto the NS surface. It is partially accumulated close to the transition region and partially expelled by the centrifugal force. By comparing Eqs. 7 and 8, we get the limiting rotational period of the NS below which the matter can accrete onto the NS surface:

$$P > P_{\rm a} = 0.01 B_9^{6/7} M_{16}^{-3/7}. \tag{9}$$

NSs with periods within this range, $P_{\rm p}$ and $P_{\rm a}$, can only accrete matter in the propeller scenario. However, for periods longer than $P_{\rm a}$, the accretion process occurs in the accretor phase. This phase is of our main interest in this paper.

III. Acceleration of hadrons

The transition region contains turbulent magnetized plasma which provides good conditions for the acceleration of hadrons. Relativistic hadrons can suffer significant energy losses due to radiative processes in collisions with dense thermal radiation from the polar cap. The maximum power available for the acceleration of particles is limited by the extracted energy in the transition region. This energy can be supplied by two mechanisms. In the case of a quasi-spherical accretion from the stellar wind, the matter has to be accelerated to the velocity of the rotating magnetosphere at $R_{\rm A}$. The rotating NS decelerates, providing energy to the turbulent region. In the case of accretion through the Lagrangian point, the matter has a large angular momentum, which has to be partially lost in the transition region in order to guarantee the accretion process up to the NS surface. The rotational energy of the accreting matter is then supplied partially to the transition region and to the NS. As a result, the NS reaches the angular momentum and accelerates. In the first case, the power which has to be transfered from the rotating NS to the accreting matter can be estimated from:

$$L_{\rm w} = \dot{M}_{\rm acc} v_{\rm rot}^2/2 \approx 10^{31} B_9^{8/7} M_{16}^{3/7} P^{-2} \quad {\rm erg\ s^{-1}}. \tag{10}$$

By Using Eq. 9, we can estimate the maximum power which can be extracted via accretion from the quasi-spherical wind,

$$L_{\rm w}^{\rm max} \approx 10^{35} B_9^{-4/7} M_{16}^{9/7} \quad {\rm erg\ s^{-1}}. \tag{11}$$

In the case of accretion through the accretion disk, the matter arrives to the transition region with the Keplerian velocity. This region is now closer to the NS surface than estimated above in $R_{\rm A}$ (see Eq. 2) by a factor $\chi \sim 0.1 - 1$ (see [5]). In order to accrete onto the NS surface, the matter from the disk has to be slowed down to the rotational velocity of the NS magnetosphere, i.e. from $v_{\rm kep}$ to $v_{\rm rot}$. Then, the maximum available power extracted in the transition region is,

$$\begin{aligned} L_{\rm d} &\approx \frac{1}{2}\dot{M}_{\rm acc}(v_{\rm kep}^2 - v_{\rm rot}^2) \\ &= L_{\rm w}^{\rm max}(\frac{1}{\chi} - \frac{\chi^2 P_{\rm a}^2}{P^2}) \quad \frac{\rm erg}{\rm s}. \end{aligned} \tag{12}$$

which gives $L_{\rm d} \approx L_{\rm w}^{\rm max}/\chi$ for $P \gg P_{\rm a}$.

A part, η, of the power, $L_{\rm w}$ or $L_{\rm d}$, can be used for the acceleration of hadrons. Below we estimate the characteristic energies of accelerated hadrons. The acceleration rate of hadrons with energy E (and Lorentz factor $\gamma_{\rm p}$) can be parametrized by a simple scaling to the Larmor radius of particles within a medium with magnetic field B,

$$\dot{P}_{\rm acc} = \frac{\xi c E}{R_{\rm L}} \approx 1.3 \times 10^6 \xi_{-1} M_{16}^{6/7} B_9^{-5/7} \quad \frac{\rm erg}{\rm s}, \tag{13}$$

where $\xi = 10^{-1}\xi_{-1}$ is the acceleration parameter, c the velocity of light, $R_{\rm L} = E/eB_{\rm A}$ the Larmor radius, and

e electron charge. The maximum energies of the accelerated hadrons are determined by the balance between the acceleration time scale and the time scale which defines the confinement of hadrons inside the turbulent region or the characteristic time scale for energy losses of accelerated hadrons.

The lower limit on the confinement time scale gives the escape time scale of hadrons from the acceleration site. It can be defined as, $\tau_{\rm esc} = R_{\rm A}/v_{\rm f} \approx 1.1 \times 10^{-3} B_9^{6/7} M_{16}^{-3/7}$ s. By comparing this time scale with the acceleration time scale, $\tau_{\rm acc} = m_{\rm p}\gamma_{\rm p}/\dot{P}_{\rm acc}$ (where $m_{\rm p}$ is the proton mass), we can estimate the Lorentz factors to which hadrons can be accelerated,

$$\gamma_{\rm p} \approx 10^6 \xi_{-1} B_9^{1/7} M_{16}^{3/7}. \quad (14)$$

This estimates do not overcome the maximum possible Lorentz factor of particles, which can be accelerated within the region with characteristic diameter $R_{\rm A}$ and magnetic field $B_{\rm A}$, defined by the condition that the Larmor radius is smaller than the Alfven radius, $R_{\rm L} < R_{\rm A}$, $\gamma_{\rm p}^{\rm max} \approx 6 \times 10^6 B_9^{-1/7} M_{16}^{4/7}$.

Hadrons with the Lorentz factors estimated in Eqs. 14 are above the threshold for pion production in collisions with thermal photons from the polar cap region equal to

$$\gamma_{\rm p\gamma}^{\rm th} \approx 1.6 \times 10^4 B_9^{-1/7} M_{16}^{-5/28}. \quad (15)$$

We can estimate the collision rate for hadrons inside the transition region

$$N_{\rm p\gamma\to\pi} = \sigma_{\rm p\gamma} c n (R_{\rm A}/v_{\rm f}) \approx 2.4 B_9^{-3/7} M_{16}^{27/28}, \quad (16)$$

where $n = n_{\rm bb}(R_{\rm cap}/((R_{\rm A} - R_{\rm NS}) + R_{\rm cap}))^2$ ($n \approx n_{\rm bb} R_{\rm cap}^2/R_{\rm A}^2$ for $R_{\rm A} \gg R_{\rm cap}$) is the density of the black body photons coming from the polar cap at the distance of the transition region $R_{\rm A}$, and $\sigma_{p\gamma} \approx 3 \times 10^{-28}$ cm^{-2} is the cross section for pion production due to a collision of relativistic proton with thermal photons.

We consider hadrons which are accelerated with a power law or a mono-energetic spectra at the transition region. In the first case hadrons with energies below the threshold for pion production in collisions with thermal photons also exist. These hadrons can only interact with the matter inside the transition region and the matter accreting onto the NS surface. We estimate the density of matter at the transition region, $\rho = \dot{M}_{\rm acc}/(\pi R_{\rm A}^2 v_{\rm f}) \approx 2.2 \times 10^{15} B_9^{-6/7} M_{16}^{10/7}$ cm^{-3}, and the interaction rate of hadrons for pion production $N_{\rm pp\to\pi} = \sigma_{\rm pp} c \rho (R_{\rm A}/v_{\rm f}) \approx 2 \times 10^{-3} M_{16}$. Therefore, hadron-hadron interactions are not efficient at the transition region. These lower energy hadrons are convected with the in-falling matter on the NS surface. They interact with much denser matter in the accretion column over the polar cap region. However, neutrinos produced in hadron-hadron collisions have on average lower energies due to large pion multiplicity (see e.g. [6]).

IV. Production of neutrinos

We calculate the spectra of muon neutrinos coming from the decay of pions produced in collisions of hadrons with the thermal radiation form the NS surface by applying a numerical code developed for the interaction of hadrons with photons within supernova envelope where the condition are quite similar (see [7]). Two types of hadron injection spectra are considered: (a) a power law differential spectrum with the spectral index 2.1 which cuts at energies estimated by Eq. 14, and (b) a mono-energetic spectrum with energies given by Eq. 14.

Note that, pions and muons (from their decay) are produced in a relatively strong magnetic field at $R_{\rm A}$. Therefore, they can suffer significant synchrotron energy losses. In order to check whether or not the synchrotron process can change the energies of the produced charged pions and muons before their decay, we calculate their synchrotron energy loss time scales and compare them with their life times. From this comparison, we put an upper limit on the Lorentz factor of pions, $\gamma_\pi^{\rm s} \approx 7 \times 10^7 B_9^{10/7} M_{16}^{-12/7}$, that are able to decay before losing a significant amount of energy. We take the effects of synchrotron energy losses of pions on the produced spectra of neutrinos in the case of their production by hadrons with the Lorentz factors above $\gamma_\pi^{\rm s}$ into account by simply replacing their γ_π by $\gamma_\pi^{\rm s}$.

For the example calculations, we fix the following parameters describing acceleration of hadrons: $\xi_{-1} = 0.1$, and $\eta = 0.1$. In Table 1, we show the muon neutrino event rates that are expected in a km^2 neutrino detector from millisecond pulsars at the distance of 5 kpc which accrete matter from the stellar wind. The typical parameters for the MSPs and the accretion rates are considered. The results are shown for a power law spectrum of hadrons (marked by *power*) and a mono-energetic spectrum (marked by *mono*). The number of neutrino events is estimated by integrating the muon neutrino spectra over the probability of their detection,

$$N_\mu = \frac{S}{(\pi D^2)} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} P_{\nu\to\mu}(E_\nu) \frac{dN_\nu}{dE_\nu dt} dE_\nu, \quad (17)$$

where $S = 1$ km^2 is the surface of the detector, D is the distance to the source, $P_{\nu\to\mu}(E_\nu)$ is the energy dependent detection probability of a muon neutrino [10], and $E_\nu^{\rm min}$ to $E_\nu^{\rm max}$ is the energy range of the produced neutrinos in our numerical calculations. The expected neutrino event rates from millisecond pulsars range from a few up to several per km^2 per yr (depending on the model). These event rates should be detected significantly by the IceCube neutrino detector or by the planned KM3NET detector on the Northern hemisphere.

V. Conclusion

We have shown that accreting milisecond pulsars can produce detectable fluxes of neutrinos by the km^3 neutrino detectors at the Earth (IceCube, KM3NET). The considered model assumes that hadrons are efficiently accelerated at the transition region in the inner pulsar

TABLE I: Neutrino event rates from a MSP at 5 kpc distance.

B [G]	M [g s^{-1}]	$\gamma_{\rm p}^{\rm max}$	P$_{\rm a}$ [ms]	N$_\nu$ [km^{-2}yr^{-1}] power	mono
3×10^8	10^{17}	2.3×10^5	13	1.8	5.1
10^9	3×10^{17}	4.3×10^5	23	5.7	5.6
3×10^9	10^{18}	8.4×10^5	36	20	5

magnetosphere which appears during the accretion process onto the neutron star.

Different factors can enhance or reduce the neutrino event rates reported in Table 1. The obvious ones are related to the distance to the source and the variable neutrino emission due to a change in the accretion rate caused e.g. by the eccentric orbit of the neutron star. Moreover, in the case of the accretion process through the accretion disk, the power available for the acceleration of particles can be enhanced by a factor of χ^{-1} (χ is typically in the range $\sim 0.1 - 1$, see Eq. 12) with respect to the case of the quasi-spherical accretion. Therefore, the neutrino event rates reported in Table 1 should be scaled as well by that factor. From another site, most of the observed millisecond pulsars belong to globular clusters. It is expected that a massive globular cluster can contain up to ~ 100 MSPs[11]. In fact, inside the globular clusters Tuc 47 and Ter 5, already $\sim 20-30$ MSP have been discovered [4]. A significant amount of the MSP cannot be discovered directly by their pulsed radio emission since they are inside compact binary systems (so called hidden MSPs[12]). These hidden MSP can become neutrino sources via the production mechanisms, that have being discussed in our model. Therefore, the neutrino event rates expected from the whole population of MSPs in a specific globular cluster can be enhanced due to the cumulative contribution from many sources.

REFERENCES

[1] Q.Z. Liu, J. van Paradijs, E.P.J. van den Heuvel 2006 A&A 455, 455
[2] Q.Z. Liu, J. van Paradijs, E.P.J. van den Heuvel 2007 A&A 469, 807
[3] S. Karino 2007 PASJ 59, 961
[4] F, Camilo, F.A. Rasio, 2005, Binary Redio Pulsars, eds. Rasio F.A., Stairs, I.H., ASP Conf. Ser. (San Francisco), 328, 147
[5] F.K. Lamb, C.J. Pethick, D. Pines 1973 ApJ 184, 271
[6] C.D. Orth, A. Buffington 1976 ApJ 206, 312
[7] J.H. Beall, W. Bednarek 2002 ApJ 569, 343
[8] P. Lipari 1993 APh 1, 195
[9] J. Ahrens, et al. 2004 APh 20, 507
[10] T.K. Gaisser, A.F. Grillo 1987 Phys. Rev D 39, 1481
[11] M. Tavani 1993 ApJ 407, 135
[12] M. Tavani 1991 ApJ 379, L69