A Rocket Model of Neutrino Jet for Pulsar Kick

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Abstract. On the basis of the neutrino emission from the isotropic $^1S_0$ neutron superfluid vortexes in neutron star interiors, we propose a rocket model of neutrino jet for the observed pulsar kick.

1. Introduction

Ever since the discovery of pulsars in 1967, astronomers are very surprised to discover that the space velocities of the pulsars are generally rather too high. Except these recycle pulsars just mentioned, of the total 94 pulsars, the percentage of the number of Single-pulsars with velocities exceed 100 km s$^{-1}$, 200 km s$^{-1}$, 300 km s$^{-1}$, 500 km s$^{-1}$ and 1000 km s$^{-1}$ are respectively 79%, 67%, 40%, 16% and 5.6%. This means that the high-velocity pulsars are rather common phenomena in interstellar space and the cosmos. The space velocities of these pulsars are far above both their progenitor stars and normal stars (about 20-40 km s$^{-1}$).

At the present stage, most of the theories conceived by astronomers to explain the unanticipated high velocities of the nascent pulsars have been established on the basis of certain spatially asymmetric cause due to fundamental physics or dynamical effect during the very short interval of supernovae explosion to form pulsars or neutron stars. Until now, four different kinds of mechanisms [1,2,3,4,5,6,7] for the observed neutron star kicks have been proposed. It seems that none of the four different kinds of mechanisms could convincingly and successfully explains the observed huge pulsar kicks. We therefore will present the idea of a gradual acceleration due to neutrino jet rocker model for the pulsar kicks in the talk.

2. A Rocket Model of Neutrino Jet for the Pulsar Kick

In 1982, Peng and his collaborators [8] proposed that neutrino cyclotron emission from the superfluid vortex neutrons may be used as a possible mechanism for pulsar spin down. Starting from this theory and making use of the spatial asymmetry of neutrino spin due to parity nonconservation in weak interaction,
we now propose a new mechanism for pulsar kicks based on a neutrino rocket model from the superfluid vortex neutrons. The main idea is as follows:

We note that neutrons in circular motion can emit a neutrino-antineutrino pair via the neutral current in the unified theory of electro-weak interaction. Similarly, the super fluid vortex neutrons can also emit neutrinos and antineutrinos [8]. The neutrons in both of these processes will lose their energy $E_{n}^{(\text{rot})}$ and angular momentum $\vec{J}_{n}$.

It is expected that the angular distributions of the neutrinos and antineutrinos are not asymmetrical due to the angular momentum loss from the neutrons, although we have $N(\nu) = N(\bar{\nu})$ according to lepton conservation. More specifically, if the angular momentum of the neutron is carried away primarily by the neutrinos, the direction of the emitted neutrinos with left hand helicity must be opposite to the original neutron angular momentum, while the neutron itself will receive a recoil along its angular momentum. Fortunately, it is shown by the very recent observational evidence that the kicks of the two youngest pulsars (the Crab pulsar and the Vela pulsar) are basically consistent with their spinning axes [7]. Hence, it is anticipated that the angular momentum of the superfluid vortex neutrons is mainly carried away by the neutrinos rather than by antineutrinos.

3. Pulsar Kick generated by Neutrino Rocket Propulsion

The neutrino luminosity due to the superfluid vortex neutrons in the neutron star interior has been derived by Peng et al. [8]. Making use of their result, we may study the acceleration of the nascent and determine the kick velocity
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Figure 2. The comparison of the calculated pulsar velocity with observation in the absence of magnetic field decay. The pulsar period $P$ is treated as the independent variable here. All the curves computed from our model (from top to down) corresponds respectively to $P_0 = 1$ ms, 1.5 ms, 2 ms and 4 ms. Here the magnetic fields is $B_{12} = 10^{12}$ gauss.

The recoil acceleration of the neutron star due to the effect of neutrino rocket propulsion as briefly discussed above may be written as $M \frac{dv}{dt} = \eta_\nu W_\nu c$, here $W_\nu$ is the power for neutrino emission from the superfluid vortex neutrons in the neutron star. $M$ is the mass of the neutron star. The effective asymmetry coefficient $\eta_\nu$ for the neutrino emission maybe estimated to be $\eta_\nu \approx 5 - 20\%$. It is found [8] that $W_\nu = bG(n)\Omega$, where $\Omega$ represents the rotating angular velocity of the neutron star. $b \approx 4.61 \times 10^{22}R_6^3$ (in c.g.s. unit), $R_6$ is the radius of the neutron star in unit of $10^6$ km. $G(n) = \frac{n}{n_0}$, where $n$ denotes the quantum number of the neutron superfluid vortexes and it decreases when the pulsar period increases during the dynamical evolution of pulsars spin down. Making a working assumption $G(n) = G(n_0)(P/P_0)^{-\beta}$ ($\beta \approx 3$), the corresponding recoil velocity of the neutron star may then be obtained by using the spin down law for the pulsars in our hybrid model. The results for the neutron star kicks with different initial periods are shown in Fig. 1 and Fig. 2. In these figures, the pulsar velocity $v$ is shown as a function of $x = P/P_0$ (more precisely $v(P/P_0) - v_0$).

We will now elaborate on some of the important and subtle points of our model. We note that the initial neutron superfluid vortex quantum number $n_0$ and the initial spinning period $P_0$ are the two most important parameters of our model. In order the neutron star to receive larger pulsar kicks of several hundred km s$^{-1}$ or even exceed 100 km s$^{-1}$ from the acceleration scenario predicated by our neutrino jet rocket mechanism, it is required that the initial vortex quantum number $n_0$ reach (500-700) for the model without magnetic field decay, or $n_0 = (5-8) \times 10^3$ for models with magnetic field decay. Such huge initial vortex quantum numbers are possible vis a vis the chaotic and violent process during which the neutron stars are born. This is because the spinning angular velocity
\( \Omega \) of the neutron star becomes much faster after the collapse due to the conservation of the angular momentum of the entire star. We easily derive the result \( \Omega_0 \geq 1.0 \times 10^4 \text{s}^{-1} \), \( P_0 < 1 \text{ ms} \). However, for a rapidly rotating stable neutron star, a considerable amount of the spinning angular momentum must have been converted into the highly chaotic and turbulent (classical) whirlpool vortexes. Moreover, it is also expected that the turbulent vortexes can be further converted into quantized superfluid vortexes with very high initial vortex quantum number \( n_0 > 10^4 \) or more provided that the temperature of the neutron star decreased down to \( T < T_{\text{trans}} = 2 \times 10^{10} \text{ K} \).

4. Main Results in Our Model

It is shown that our theory predicts naturally the gradual acceleration of the nascent pulsars during the early stage from \( P_0 \) to \( 10P_0 \) (about 200-300 years, where \( P_0 \) denotes the initial spinning period) and that huge natal kicks of neutron stars exceed 1000 km s\(^{-1}\) follows very nicely from our model. We have investigated the acceleration scenario during the early stage of pulsar evolution in terms of the initial periods and the initial magnetic fluid. In particular, (a) the observed alignment of the pulsar kicks with their spinning axes may be interpreted naturally. (b) All high velocity pulsars with spatial velocities higher than 100 km s\(^{-1}\) have initial periods shorter than (2-3) ms; moreover, the initial periods of these pulsar with huge kicks exceed 1000 km s\(^{-1}\) are shorter than 0.8 ms. (c) For the same magnetic fields, the initial periods of the high velocity pulsars are short. (d) For the same initial spinning pulsar periods, the high velocity pulsars have weaker magnetic field.

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