Pulsar velocities and dark matter hint at a singlet neutrino

Alexander Kusenko
Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547
and RIKEN-BNL Center, Brookhaven National Laboratory, Upton, NY 11973

Abstract

Two astrophysical puzzles, the origin of pulsar velocities and that of dark matter, may have a simultaneous explanation if there exists a sterile neutrino with a mass in the 1–20 keV range and a small mixing ($\sin \theta \sim 10^{-4}$) with the electron neutrino. Although the mixing is too small for direct detection, future observations of the X-ray telescopes, as well as the gravity wave detectors, such as LIGO and LISA, may be able to confirm or rule out the existence of such a neutrino.

1. Introduction

Pulsar velocities range from 100 to 1600 km s$^{-1}$ [1, 2]. They present a long-standing puzzle. According to numerical simulations of supernova explosions [3], the asymmetries in the core collapse could not account for a kick velocity of more than 300-600 km s$^{-1}$. Although the average pulsar velocity is in this range [1], there is a substantial population of pulsars with velocities in excess of 700 km/s, while as many as 15% of all pulsars have speeds over 1000 km s$^{-1}$ [2].

It has been suggested that an asymmetric emission of electroweak-singlet neutrinos from a cooling neutron star could explain the pulsar velocities [4, 5]. Since most of the supernova energy is carried away by neutrinos, only a few percent asymmetry is sufficient. The range of parameters (mass and mixing angle) consistent with this explanation overlaps with the allowed region for the singlet neutrinos to make up the cosmological dark matter [5, 6, 7].

Let us consider a singlet (or sterile) neutrino $\nu_s$ that has a small mixing with the electron neutrino $\nu_e$. The mixing angle $\theta$ we will consider is $10^{-5} - 10^{-4}$, much smaller than those accessible to laboratory experiments. However, neutrino oscillations could result in a production of such a neutrino in the early universe, as well as in a supernova.

There are actually two possible mechanisms for the pulsar kick due to the sterile neutrinos. One is based on off-resonance production and requires the
singlet neutrino to have a mass of a few keV [5]. The other possibility is a resonant \( \nu_e \to \nu_s \) conversion, which can occur for the mass of several to 20 keV. Let us briefly discuss both of these possibilities.

2. Off-resonance emission.

In a strong magnetic field inside the neutron star, the electroweak (urca) processes produce neutrinos with a sizable asymmetry. However, the asymmetry in production does not cause an asymmetry in emission of ordinary, active neutrinos because numerous re-scatterings of the trapped neutrinos wash out the asymmetry [8]. However, if the urca processes produced some other particles, with a very small scattering cross section, these particles could escape from the neutron star with an asymmetry equal to their production asymmetry, hence giving the neutron star a recoil. This is what happens if a sterile neutrino exists and if it has a small mixing with the electron neutrino [5].

For a sufficiently small mixing angle between \( \nu_e \) and \( \nu_s \), only one of the two mass eigenstates, \( \nu_1 \), is trapped. The orthogonal state, \( |\nu_2\rangle = \cos \theta_m |\nu_s\rangle + \sin \theta_m |\nu_e\rangle \), escapes from the star freely. This state is produced in the same basic urca reactions \( (p+e^- \leftrightarrow \nu_e + n \text{ and } n+e^+ \leftrightarrow \bar{\nu}_e + p) \) with the effective Lagrangian coupling equal the weak coupling times \( \sin \theta_m \). The region of parameters consistent with the pulsar kick and also with the existing constraints is shown as region “2” in Fig. 1 [5].

3. On-resonance emission

Resonant production of sterile neutrinos can cause the pulsar kick as well, for a somewhat different range of masses and mixings. The position of the resonant conversion \( \nu_e \to \nu_s \) depends on the direction of the magnetic field relative to the direction of the neutrino momentum. Therefore, the sterile neutrinos escape from different densities, \( i.e. \), from different depths, depending on their direction. Due to the temperature gradient in the star, the average neutrino energy varies with depth, and so the momentum distribution of emitted sterile neutrinos is anisotropic. This mechanism was proposed in Ref. [4] and was a straightforward generalization of the mechanism proposed earlier [9] for active neutrinos.* (The

*I note in passing that the pulsar kick mechanism based on neutrino oscillations [9, 4] was criticized erroneously by Janka and Raffelt [10], who got an incorrect result by neglecting the differences in the neutrino opacities for different flavors and by assuming that the flux of neutrinos remained constant through the core and the neutrinospheres. The latter assumption is wrong because both the neutrino absorptions [11] and the \( (1/r^2) \) effect of the spherical geometry [12] result in a non-constant flux of the outgoing neutrinos. These two errors of Janka and Raffelt were pointed out by us [11] and by Barkovich et al. [12], respectively.)
Fig. 1. The region of parameters consistent with the pulsar kicks and dark matter. Also shown is the region accessible to Chandra [13]. In region 1 the pulsar kick is due to the resonant conversions $\nu_e \rightarrow \nu_s$ [4]. In region 2, the production of singlet neutrinos off resonance can explain the observed pulsar velocities [5]. The lepton asymmetry $L$ of the universe may affect the allowed parameter range for dark matter. Two narrow bands correspond to dark matter for $L = 0$ and $L = 0.01$.

mechanism using the active neutrinos alone does not work because the required neutrino mass is too large [9].

4. Prospects for detection

The mixing angles shown in Fig. 1 are too small for direct detection. However, there are ways to confirm or rule out this range of the singlet masses and mixing angles. Sterile neutrinos can decay into a (lighter) active neutrino and a photon. The lifetime of the sterile neutrinos exceeds the age of the universe by many orders of magnitude, but there is, nevertheless, a signal that X-ray telescopes can detect [13]. Chandra observations are sensitive to part of the region shown in Fig. 1, and Constellation-X may be able cover the entire range, or, at least, a larger part of it.

A pulsar being accelerated by an asymmetric emission of neutrinos gener-
ates gravity waves \[14\] [15]. One can think of it as a rotating source of a neutrino jet superimposed on a spherically symmetric distribution of neutrinos and spinning around some axis. This rotating jet produces gravity waves, which may be detected in the event of a nearby supernova \[15\].

To summarize, a singlet neutrino could explain both the pulsar kicks and the dark matter simultaneously. Introduction of such a particle is probably the most economical extension of the Standard Model that makes it consistent with dark matter.

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