PULSAR KICKS AND DARK MATTER FROM A STERILE NEUTRINO

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The observed velocities of radio pulsars, which range in the hundreds kilometers per second, and many of which exceed 1000 km/s, are not explained by the standard physics of the supernova explosion. However, if a sterile neutrino with mass in the 1–20 keV range exists, it would be emitted asymmetrically from a cooling neutron star, which could give it a sufficient recoil to explain the pulsar motions. The same particle can be the cosmological dark matter. Future observations of X-ray telescopes and gravitational wave detectors can confirm or rule out this explanation.

1. Introduction

Pulsar velocities range from 100 to 1600 km/s\[^{1,2}\]. Their distribution leans toward the high-velocity end, with about 15% of all pulsars having speeds over (1000 km/s).\[^{2}\] The origin of these velocities is a long-standing puzzle. Pulsars are born in supernova explosions, so it would be natural to look for an explanation in the dynamics of the supernova.\[^{3}\] However, state-of-the-art 3-dimensional numerical calculations\[^{4}\] show that even the most extreme asymmetric explosions do not produce pulsar velocities greater than 200 km/s. Earlier 2-dimensional calculations\[^{5}\] claimed a maximal pulsar velocity up to 500 km/s to be possible. Of course, even this size of the kick was way too small to explain the large population of pulsars with speeds above 1000 km/s.

Given the absence of a “standard” explanation, one is compelled to consider alternatives, possibly involving new physics. One of the reasons why the standard explanation fails is because most of the energy is carried

\[^{*}\]Work partially supported by the DOE grant DE-FG03-91ER40662 and the NASA ATP grant NAG5-13399.
away by neutrinos, which escape isotropically. The remaining energy must be distributed with a substantial asymmetry to account for the large pulsar velocities. In contrast, only a few per cent anisotropy in the distribution of neutrinos would give the pulsar a kick of required magnitude.

Neutrinos are produced anisotropically, but they escape isotropically. The asymmetry in production comes from the asymmetry in the basic weak interactions in the presence of a strong magnetic field. Indeed, if the electrons and other fermions are polarized by the magnetic field, the cross section of the urca processes, such as $n + e^+ \rightarrow p + \bar{\nu}_e$ and $p + e^- \rightarrow n + \nu_e$, depends on the orientation of the neutrino momentum. Depending on the fraction of the electrons in the lowest Landau level, this asymmetry can be as large as 30%, much more than one needs to explain the pulsar kicks. However, this asymmetry is completely washed out by scattering of neutrinos on their way out of the star.

If, however, the same interactions produced a particle which had even weaker interactions with nuclear matter than neutrinos, such a particle could escape the star with an asymmetry equal its production asymmetry.

It is intriguing that the same particle can be the dark matter.

The simplest realization of this scenario is a model that adds only one singlet fermion to the Standard Model. The SU(2) × U(1) singlet, a sterile neutrino, mixes with the usual neutrinos, for example, with the electron neutrino.

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 ($\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$) with the effective Lagrangian coupling equal the weak coupling times $\sin \theta_m$.

We will consider two ranges of parameters, for which the $\nu_e \rightarrow \nu_s$ oscillations occur on or off resonance. First, let us suppose that a resonant oscillation occurs somewhere in the core of the neutron star. Then the asymmetry in the neutrino emission comes from shift in the resonance point depending on the magnetic field. Second, we will consider the off-resonance case, in which the asymmetry comes directly from the weak processes, as described above.
2. Resonant, Mikheev-Smirnov-Wolfenstein oscillations

Neutrino oscillations in a magnetized medium are described by an effective potential

\[ V(\nu_s) = 0 \]
\[ V(\nu_e) = -V(\bar{\nu}_e) = V_0 (3 Y_e - 1 + 4 \bar{Y}_e) \] (2)
\[ V(\nu_{\mu,\tau}) = -V(\bar{\nu}_{\mu,\tau}) = V_0 (Y_e - 1 + 2 \bar{Y}_e) + \frac{eG_F \sqrt{2}}{\pi^2} \left( \frac{3 N_e}{\pi^4} \right)^{1/3} \frac{k \cdot B}{|k|} \] (3)

where \( Y_e \) (\( \bar{Y}_e \)) is the ratio of the number density of electrons (neutrinos) to that of neutrons, \( B \) is the magnetic field, \( k \) is the neutrino momentum, \( V_0 = 10 \text{eV} (\rho/10^{14} \text{g cm}^{-3}) \). The magnetic field dependent term in equation (4) arises from polarization of electrons and not from a neutrino magnetic moment, which is small and which we will neglect.

The condition for resonant MSW oscillation \( \nu_i \leftrightarrow \nu_j \) is

\[ \frac{m_i^2}{2k} \cos 2\theta_{ij} + V(\nu_i) = \frac{m_j^2}{2k} \cos 2\theta_{ij} + V(\nu_j) \] (5)

where \( \nu_{i,j} \) can be either a neutrino or an anti-neutrino.

In the presence of the magnetic field, the condition (4) is satisfied at different distances \( r \) from the center, depending on the value of the \( (k \cdot B) \) term in (4). The average momentum carried away by the neutrinos depends on the temperature of the region from which they escape. The deeper inside the star, the higher is the temperature during the neutrino cooling phase. Therefore, neutrinos coming out in different directions carry momenta which depend on the relative orientation of \( k \) and \( B \). This causes the asymmetry in the momentum distribution.

The surface of the resonance points is

\[ r(\phi) = r_0 + \delta \cos \phi, \] (6)

where \( \cos \phi = (k \cdot B)/k \) and \( \delta \) is determined by the equation \( (dN_\nu(r)/dr)\delta \approx e (3N_e/\pi^4)^{1/3} B \). This yields

\[ \delta = \frac{e \mu_e}{\pi^2} B \left/ \frac{dN_\nu(r)}{dr} \right., \] (7)

where \( \mu_e \approx (3\pi^2N_e)^{1/3} \) is the chemical potential of the degenerate (relativistic) electron gas.
Assuming a black-body radiation luminosity $\propto T^4$, the asymmetry in momentum distribution is

$$\Delta k = \frac{4e}{3\pi^2} \frac{\mu_e}{T} \frac{dT}{dN_n} B.$$  \hspace{1cm} (8)

To calculate the derivative in (8), we use the relation between the density and the temperature of a non-relativistic Fermi gas. Finally,

$$\Delta k = \frac{4e\sqrt{2}}{\pi^2} \frac{\mu_e\mu_n^{1/2}}{m_e^{3/2}T^2} B = 0.01 \left( \frac{B}{3 \times 10^{15} G} \right)$$ \hspace{1cm} (9)

if the neutrino oscillations take place in the core of the neutron star, at density of order $10^{14}$ g cm$^{-3}$. The neutrino oscillations take place at such a high density if one of the neutrinos has mass in the keV range, while the other one is much lighter. The magnetic field of the order of $10^{15} - 10^{16}$ G is quite possible inside a neutron star, where it is expected to be higher than on the surface. (In fact, some neutron stars, dubbed magnetars, appear to have surface magnetic fields of this magnitude.)

Some comments are in order. First, a similar kick mechanism, based entirely on active neutrino oscillations (and no steriles) could also work if the resonant oscillations took place between the electron and tau neutrinospheres\cite{13}. This, however, would require the mass difference between two neutrinos to be of the order of 100 eV, which is ruled out. Second, the neutrino kick mechanism was criticized incorrectly by Janka and Raffelt\cite{14}. It was subsequently shown by several authors\cite{15,16} that Janka and Raffelt made several mistakes, which is why their estimates differ from eq. (9).

3. Off-resonant oscillations

For somewhat lighter masses, the resonant condition is not satisfied anywhere inside the star. In this case, however, the off-resonant production of sterile neutrinos in the core can occur through ordinary urca processes. A weak-eigenstate neutrino has a $\sin^2 \theta$ admixture of a heavy mass eigenstate $\nu_2$. Hence, these heavy neutrinos can be produced in weak processes with a cross section suppressed by $\sin^2 \theta$.

Of course, the mixing angle in matter $\theta_m$ is not the same as it is in vacuum, and initially $\sin^2 \theta_m \ll \sin^2 \theta$. However, as Abazajian, Fuller, and Patel\cite{10} have pointed out, in the presence of sterile neutrinos the mixing angle in matter quickly evolves toward its vacuum value. When $\sin^2 \theta_m \approx$
\[ \sin^2 \theta \], the production of sterile neutrinos is no longer suppressed, and they can take a fraction of energy out of a neutron star.

Sterile neutrinos escape with a sizable asymmetry due to weak interactions of fermions polarized by the magnetic field. (Once again, we neglect a neutrino magnetic moment and consider only the matter fermions.) The resulting asymmetry can explain the pulsar kicks if the mass and mixing angle fall inside region 2 in Fig. 1.

4. Sterile neutrinos as dark matter; observational consequences

The parameter space allowed for the pulsar kicks overlaps nicely with that of dark-matter sterile neutrinos. Sterile neutrinos in this range may soon be discovered. Relic sterile neutrinos with mass in the 1-20 keV range can decay into a lighter neutrino and a photon. The X-ray photons should be detectable by the X-ray telescopes. Chandra and XMM-Newton can exclude part of the parameter space. The future Constellation-X can
probably explore the entire allowed range of parameters.

In the event of a nearby supernova, the neutrino kick can produce gravity waves that could be detected by LIGO and LISA.[18,19] Active-to-sterile neutrino oscillations can give a neutron star a kick. However, if a black hole is born in a supernova, it would not receive a kick, unless it starts out as a neutron star and becomes a black hole later, because of accretion. (The latter may be what happened in SN1987A, which produced a burst of neutrinos, but no radio pulsar.) If the central engines of the gamma-ray bursts are compact stars, the kick mechanism acting selectively on neutron stars and not black holes could probably explain the short bursts as interrupted long bursts.[20]

Since one does not expect a significant correlation between the magnetic field inside a hot neutron star (while this field is, presumably, growing via the dynamo effect) and the eventual exterior field of a radio pulsar, the neutrino kick mechanism does not predict any $B - v$ correlation.

To summarize, the nature of cosmological dark matter is still unknown. We know that at least one particle beyond the Standard Model must exist to account for dark matter. This particle may come as part of a “package” if supersymmetry is right. However, it may be that the dark matter particle is simply an SU(2)$\times$U(1) singlet fermion, which has a small mixing with neutrinos. In the latter case, the same dark-matter particle would be emitted anisotropically from a supernova with an asymmetry sufficient to explain the pulsar kick velocities.

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