SOME ASTROPHYSICAL IMPLICATIONS OF EXPERIMENTALLY
FAVORED NEUTRINO MASSES AND MIXINGS

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ABSTRACT

Positive evidence for neutrino oscillations is mounting from the solar and atmospheric neutrino anomalies and the LSND experiment. Accordingly, the neutrino mass differences appear to lie in the sub-eV range and at least some of the mixing angles appear to be large. We explore some of the consequences of this picture for supernova (SN) physics and cosmology. In particular, we discuss if a conflict between the solar vacuum solution and the SN 1987A signal can be avoided, and the role of future cosmic microwave background measurements to reveal the presence of a cosmological hot dark matter component.

1. Introduction

The impressive up-down asymmetry observed at Superkamiokande leaves little room for doubt that the atmospheric neutrino anomaly is indeed caused by oscillations of muon neutrinos into nearly maximally mixed tau or sterile neutrinos. Likewise, it has become more and more difficult to avoid neutrino oscillations as an explanation for the solar neutrino puzzle. Only the LSND evidence for $\bar{\nu}_e-\bar{\nu}_\mu$-oscillations has come under increasing pressure from the advancing exclusion limit of the KARMEN experiment, but thus far remains a viable hypothesis.

These results (Table 1) suggest three plausible, qualitatively different scenarios. If LSND is wrong, solar and atmospheric neutrinos alone indicate very small differences between the neutrino masses. We may then have a hierarchical mass scheme with the largest mass eigenvalue below 0.1 eV. Or else we may have a degenerate scheme where all three masses are large relative to their splittings. Either way, at least some (and perhaps all) of the mixing angles are large. If the LSND signal is caused by oscillations after all, we need a sterile neutrino in addition to the three sequential ones. It is then most natural to expect a mass scheme with two small and two nearly degenerate “large” eigenstates, where the separation between the two pairs is given by LSND. Within the pairs we can have large mixing.

If we take any of these scenarios seriously, what does this imply for the possible role of neutrinos in astrophysics and cosmology? Apart from the direct experimental observations of solar and atmospheric neutrinos, the classic astrophysical environments where massive neutrinos and their oscillations can play a crucial role are supernovas...
and the early universe. Consequently, we shall explore some of the implications of the experimentally favored neutrino masses and mixings for SN physics and cosmology.

2. Cosmic Background Neutrinos

It is exactly twenty-five years ago that Cowsik and McClelland put forth the idea that cosmic background neutrinos, if they had a small mass, could provide the dark matter of the universe. However, it was quickly realized that low-mass collisionless particles do not easily cluster on small scales. A simple phase-space argument (“Tremaine-Gunn-limit”) reveals that neutrino masses would have to exceed about 20–30 eV to provide the dark matter of spiral galaxies, and 100–200 eV for dwarf galaxies. On the other hand, the age of the universe exceeds about $12 \times 10^9$ years which sets an upper limit to the cosmic matter density, translating into an upper limit of about 30–40 eV for the sum of all neutrino masses. Evidently, neutrinos cannot be the dark matter on all scales even though one might imagine that, by a squeeze, they could still be the dark matter in spiral galaxies. However, if we take the experimental indications for oscillations seriously, the neutrino mass differences are small on the scale of 10 eV. Even if we use the largest LSND-favored $\Delta m^2$ of about 10 eV$^2$, it corresponds to $\Delta m \approx 0.5 \text{ eV}$ for $m \approx 10 \text{ eV}$. Therefore, all neutrino masses, including that of a putative sterile state, are nearly degenerate so that the cosmological limit is $m \sim <10^{-15}$ eV for each flavor separately, exacerbating the galactic phase-space problem for neutrino dark matter.

Today it has become difficult to avoid the standard theory of cosmological structure formation where an essentially flat power spectrum of primordial density fluctuations is amplified by the gravitational instability mechanism. Low-mass neutrinos would stream freely for a long time after their decoupling in the early universe (“hot dark matter”), erasing small-scale density perturbations and thus preventing structures to form below the supercluster scale. Again, low-mass neutrinos do not seem suitable as dark-matter candidates.
Standard cold dark matter (SCDM) fares much better, but it has the opposite problem of overproducing small-scale structure. One intriguing remedy is to invoke a small fraction (say 20%) of hot dark matter in a “hot plus cold dark matter” (HCDM) scenario. The small-scale power spectrum of the cosmic matter-density fluctuations will be measured with unprecedented precision by the Sloan Digital Sky Survey. It was recently shown that these measurements may well be sensitive down to the lower end of LSND-inspired neutrino masses. Even presently available data seem to favor a HCDM cosmology not only over SCDM, but also over a variety of modified CDM scenarios such as an undercritical (open) universe (OCDM), a tilted primordial fluctuation spectrum (TCDM), or CDM with a cosmological constant (ΛCDM). On the other hand, the Hubble diagram of type Ia supernovae, which was recently extended to high redshifts, appears to favor a significant Λ-term and thus a ΛCDM universe.

A cosmological role for neutrinos as a cosmological hot dark matter component in a HCDM scenario fits in with two of the neutrino mass schemes discussed in the introduction. We may have three nearly mass-degenerate neutrino states with a common mass scale of, say, 1–2 eV. This possibility implies that νe has a mass in this range, making it potentially accessible to searches in neutrinoless ββ and tritium β-endpoint experiments. However, a truly positive indication for eV-range neutrino masses is provided only by LSND so that the HCDM hypothesis is closely intertwined with a four-flavor picture involving sterile neutrinos. They would be partially excited in the early universe by oscillations from those sequential neutrinos with which they are mixed so that there would be a nonstandard radiation component in addition to the hot dark matter contribution. Standard big-bang nucleosynthesis arguments already constrain an additional radiation content equivalent to more than one extra neutrino species so that a sterile neutrino which solves the atmospheric neutrino anomaly by νµ-νs oscillations is already difficult to accommodate.

Besides the impact on the large-scale structure of the universe, a hot dark matter component would leave its imprint in the temperature variations of the cosmic microwave background radiation (CMBR). The anticipated sky maps of the future MAP and PLANCK satellite missions have already received advance praise as the “Cosmic Rosetta Stone” because of the wealth of cosmological precision information they are expected to reveal.

CMBR sky maps are characterized by their fluctuation spectrum \( C_ℓ = \langle a_{ℓm} a_{ℓm}^* \rangle \) where \( a_{ℓm} \) are the coefficients of a spherical-harmonic expansion. Figure 1 (solid line) shows \( C_ℓ \) for standard cold dark matter (SCDM) with \( h = 0.5 \) for the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\), \( Ω_M = 1 \) and \( Ω_B = 0.05 \) for the matter and baryon content, a Harrison-Zeldovich spectrum of initial density fluctuations, ignoring reionization, and taking \( N_{eff} = 3 \) for the effective number of thermal neutrino degrees of freedom. As a dotted line the power spectrum is shown for \( N_{eff} = 3 \), and as a dashed line if two of them carry a small mass such as to contribute 10% of hot dark matter. In the lower panel, the relative difference to the standard case is shown.
Fig. 1. Top: CMBR fluctuation spectrum for SCDM with $h = 0.5$, $\Omega_M = 1$, $\Omega_B = 0.05$, and $N_{\text{eff}} = 3$ (solid line). The dotted line is for $N_{\text{eff}} = 4$, and the dashed line when two of these four neutrinos have equal masses corresponding together to $\Omega_{\text{HDM}} = 0.1$ ($\Omega_{\text{CDM}} = 0.85$). Bottom: Relative difference of these nonstandard models to SCDM. The shaded band represents the cosmic variance. (Figure from Hannestad and Raffelt.)

together with the “cosmic variance” (shaded region) which gives us a rough estimate of the best one can hope to achieve with the forthcoming experiments. We probably have to wait for these precision experiments before the presence or absence of neutrino dark matter, with or without an extra radiation component, can be finally settled.

In summary, it is conceivable, and even favored by current cosmological data, that neutrinos with eV-masses play a role as a hot dark matter component. This hypothesis fits nicely with the LSND result which is, however, under attack from the KARMEN non-observation of oscillations. If LSND is eventually proven wrong we are still left with the possibility of a degenerate three-flavor mass scheme for which one would not have to worry about extra contributions to the cosmic radiation density. It is also possible, however, that neutrinos do have small masses, but that they obey a hierarchy with the largest scale below 0.1 eV as suggested by the atmospheric neutrino
anomaly. It would be the ultimate irony if the Superkamiokande announcement that neutrinos do oscillate, twenty-five years after Cowsik and McClelland’s seminal paper, would turn into the beginning of the end of neutrino dark matter!

3. Supernova Neutrinos

As the oscillation interpretation of the atmospheric neutrino anomaly was put onto firmer ground by the Superkamiokande results, the perception of the solar neutrino anomaly has also changed. First, the phenomenon of oscillations has simply become more real and acceptable. Second, the large mixing angle needed for atmospheric neutrinos has propelled the solar vacuum solution from a somewhat obscure also-ran to a bit of a frontrunner. Variations of bi-maximal mixing scenarios are very much en vogue these days!

The assumption of essentially maximal mixing between $\nu_e$ and the two other flavors could have important ramifications for supernova physics. Immediately after the core collapse of a massive star at the end of its life, neutrinos are trapped, which implies that the electron-lepton number is almost as large as that of the progenitor’s iron core of about $Y_e = 0.35$ electrons per baryon, implying highly degenerate Fermi seas of electrons and electron neutrinos. The lepton number is thought to be lost on a diffusion timescale of about 1 s. One might think that the large electron-lepton number violation implied by maximal $\nu_e$ mixing with $\nu_\mu$ and $\nu_\tau$ would quickly lead to a redistribution of the electron-lepton number among all flavor, creating degenerate seas of muons and all neutrino flavors.

However, this is not so because the usual “quantum-damping” of the flavor “polarization” by oscillations and collisions is proportional to $\sin^2 2\theta$ and the collision rate. The large difference between the refractive index of $\nu_e$ and the other flavors

![Fig. 2. In the hatched range of mass differences and vacuum mixing angles, flavor equilibrium between $\nu_e$ and $\nu_\mu$ or $\nu_\tau$ would be achieved in a SN core within 1 s of collapse.](image)
caused by the medium “de-mixes” them enough to slow down the flavor conversion very much, i.e. the in-medium mixing angle becomes very small. Before the lepton number is lost by diffusion within about 1 s, flavor equilibrium is reached only if the mixing parameters lie in the hatched region of Fig. 2. Thus, the matter effect prevents maximal neutrino mixing from playing havoc with the neutrino flavors in a SN core as long as the neutrino masses obey the cosmological mass limit.

Another issue arises in the context of the interpretation of the SN 1987A neutrino signal. It is usually thought that a SN emits the binding energy of the newly formed compact star, $E_b = 1.5 - 4.5 \times 10^{53}$ erg, (1) almost entirely in the form of neutrinos. It is thought that the energy is equally distributed among the flavors, but with different spectra which are characterized by the average energies (2)

$$\langle E_\nu \rangle = \begin{cases} 
10-12 \text{ MeV} & \text{for } \nu_e, \\
14-17 \text{ MeV} & \text{for } \bar{\nu}_e, \\
24-27 \text{ MeV} & \text{for } \nu_\mu, \tau \text{ and } \bar{\nu}_\mu, \tau, 
\end{cases}$$

i.e. $\langle E_\nu \rangle \approx \frac{2}{3} \langle E_{\bar{\nu}_e} \rangle$ and $\langle E_\nu \rangle \approx \frac{5}{3} \langle E_{\nu_e} \rangle$ for the other flavors. A partial conversion between, say, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ due to oscillations would “stiffen” the $\bar{\nu}_e$ spectrum observable at Earth. (We will always take $\bar{\nu}_e$-$\bar{\nu}_\mu$-oscillations to represent either $\bar{\nu}_e$-$\bar{\nu}_\mu$-oscillations or $\bar{\nu}_e$-$\bar{\nu}_\tau$-oscillations.) Put another way, some of the SN 1987A $\bar{\nu}_e$’s observed at the Kamiokande and IMB detectors would have been oscillated $\bar{\nu}_\mu$’s which should have been correspondingly more energetic.

A maximum-likelihood analysis of the $\bar{\nu}_e$ spectral temperature and neutron-star binding energy inferred from the Kamiokande and IMB data (Fig. 3) reveals that even in the no-oscillation case (the $\tau = 1$ contour) there is only marginal overlap with the theoretical expectation of Eqs. (1) and (2). Essentially the observed neutrinos were softer than expected, especially at Kamiokande. Including a partial swap of the spectra exacerbates this problem in that the expected energies should have been even higher. In Fig. 3 we show 95% likelihood contours for the inferred $\bar{\nu}_e$ spectral temperature $T_{\bar{\nu}_e} = \langle E_{\bar{\nu}_e} \rangle / 3$ and the neutron-star binding energy $E_b$ for maximum $\bar{\nu}_e$-$\bar{\nu}_\mu$-mixing and for several assumed values $\tau = T_{\bar{\nu}_\mu} / T_{\bar{\nu}_e}$ for the relative spectral temperature between $\bar{\nu}_\mu$ and $\bar{\nu}_e$. Even for moderate spectral differences a maximum mixing between $\bar{\nu}_e$ and the other flavors appears to cause a conflict with the SN 1987A data, ostensibly excluding the solar vacuum solution.

However, the SN 1987A data and the solar vacuum solution could well be compatible if the spectral differences between the different flavors had been theoretically overestimated in the past. These differences arise because the opacities are different for the different flavors—the electron-flavored neutrinos are primarily trapped by charged-current processes of the type $\nu_e n \leftrightarrow pe^-$ or $\bar{\nu}_e p \leftrightarrow ne^+$ while the other flavors scatter by neutral currents mostly on nucleons and thus decouple in deeper
Fig. 3. Best-fit values for the spectral $\bar{\nu}_e$ temperature $T_{\bar{\nu}_e}$ and the neutron-star binding energy $E_b$, as well as contours of constant likelihood which correspond to 95% confidence regions. In each case a joint analysis between the Kamiokande and IMB detectors was performed with $\sin^2 2\theta_0 = 1$ for the vacuum mixing angle and the indicated relative $\bar{\nu}_\mu$ temperature $\tau$. The no-oscillation case is equivalent to $\tau = 1$. The hatched region corresponds to the theoretical predictions of Eqs. (1) and (2). [Plot from Jegerlehner, Neubig and Raffelt.]

layers at higher temperatures. The non-electron flavored neutrinos escape from their “transport sphere” where scattering processes are no longer effective. However, most critical for their spectrum is the deeper-lying “energy sphere” where they last exchange energy with the medium; the scattering on nucleons was usually treated as being ineffective at energy transfer because recoils are suppressed by the large nucleon mass. Therefore, the energy sphere was defined by electron scattering $\nu e^- \rightarrow e^- \nu$ while $e^+ e^- \rightarrow \nu \bar{\nu}$ was taken as the dominant production process.

However, this approximation is strictly incorrect. It was recently shown that the dominant pair-process is nucleonic bremsstrahlung $NN \rightarrow NN\nu\bar{\nu}$ while the dominant energy-exchange process is inelastic neutrino-nucleon scattering $\nu NN \rightarrow NN\nu$ and recoils in $\nu N \rightarrow N\nu$. Including these dominant energy-exchange processes clearly has the effect of making the $\bar{\nu}_\mu$ spectrum more similar to the $\bar{\nu}_e$ one. A quantitative estimate suggests that the remaining spectral differences may be small enough to avoid any conflict between the SN 1987A data and the solar vacuum solution. Of course, a self-consistent calculation of the neutrino fluxes and spectra with the correct microphysics is needed to substantiate this conclusion.

The main point that can be raised at the present time is that the canonical large spectral differences between the different neutrino flavors emitted from a SN core are rather questionable and thus cannot be used for far-reaching conclusions regarding the SN 1987A signal interpretation. Likewise, a variety of neutrino-oscillation issues in SN physics, from r-process nucleosynthesis to pulsar kicks, would be affected by a significant revision of the flavor-dependence of SN neutrino spectra.
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