Neutrino Oscillation Above a Black Hole Accretion Disk

A. Malkus[*], J. P. Kneller[*], G. C. McLaughlin[*] and R. Surman[†]

[*]*Department of Physics, North Carolina State University, Raleigh, NC 27695 USA.*
[†]*Department of Physics and Astronomy, Union College, Schenectady, NY 12308 USA*

Abstract. We examine neutrino oscillations in the context of an accretion disk surrounding a black hole. Because accretion disks produce large quantities of neutrinos, they may be home to interesting neutrino oscillation as well. We model accretion disks associated with stellar collapse for the sake of understanding neutrino oscillations. We find that the neutrino oscillations include phenomena seen in the protoneutron star setting as well as phenomena not seen elsewhere.

Keywords: neutrino mixing, neutrino-neutrino interaction, accretion disk
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INTRODUCTION

Neutrino-neutrino interactions have been studied in the contexts of the early universe [1, 2, 3, 4, 5], in supernovae [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 17, 16, 18, 19, 20, 21, 22] and once in accretion disks [23]. There, the studies of neutrino oscillations have shown a wide array of possible behaviors. The supernova setting in particular is interesting because it may show the effects of three different potentials. First, the neutrinos participate in vacuum oscillations. Second, supernovae have some density of electrons from which neutrinos can scatter, gaining an oscillation potential. Third, neutrinos may scatter off other neutrinos, resulting in a potential due to large neutrino densities. Accretion disks as well have the opportunity for all three of these potentials to influence neutrino oscillation. In these proceedings, we examine the neutrino oscillations above an accretion disk from stellar collapse. There, we study the effects from the three types of potentials that appear in the supernova case and see similar effects. We also see effects that are not present in the supernova case. A more thorough examination can be found in [24].

NEUTRINO OSCILLATIONS

Neutrino oscillations have been studied since their proposal by Pontecorvo [25]. In the ensuing decades, three major influences on the oscillation pattern have been studied. We articulate each of them in equation (1), which shows a generalized two-flavor Schroedinger-like equation for neutrino oscillation. While the computations in these proceedings use three-flavors, two flavors are useful to understand the behavior. The amplitude that a neutrino is in the ν_e flavor is $\psi_e(t)$ and the amplitude that it is in the ν_μ flavor is $\psi_\mu(t)$. Then the probability that the neutrino at time t is in the electron flavor is $P_{\nu_e\to\nu_e}(t) = |\psi_e(t)|^2$. Because in the following calculations the neutrinos all began in the electron flavor, we call $P_{\nu_e\to\nu_e}(t)$ the "survival probability."

$$i\frac{d}{dt}\begin{pmatrix}\psi_e(t)\\ \psi_\mu(t)\end{pmatrix} = \begin{pmatrix}\frac{V_e}{2}-\frac{\delta m^2}{4E}\cos 2\theta+\frac{V_{\nu_e}-V_{\bar{\nu}_e}+V_{\bar{\nu}_\mu}-V_{\nu_\mu}}{2} & \frac{\delta m^2}{4E}\sin 2\theta + V^*_{\nu_e\nu_\mu}\\ \frac{\delta m^2}{4E}\sin 2\theta + V_{\nu_e\nu_\mu} & \frac{\delta m^2}{4E}\cos 2\theta - \frac{V_e}{2} - \frac{V_{\nu_e}-V_{\bar{\nu}_e}+V_{\bar{\nu}_\mu}-V_{\nu_\mu}}{2}\end{pmatrix}\begin{pmatrix}\psi_e(t)\\ \psi_\mu(t)\end{pmatrix} \quad (1)$$

Primarily, in low density media, oscillations are controlled by the vacuum parameters of neutrino mixing that exist independent of setting. These vacuum parameters determine most of the oscillation pattern over short distances through low denisity media, like the oscillations measured in terrestrial reactor and neutrino beam experiments. In equation (1), the contributions to the oscillation from the vacuum parameters are $\frac{\delta m^2}{4E}\cos 2\theta$ and $\frac{\delta m^2}{4E}\sin 2\theta$ on the diagonal and off-diagonal respectively.

Secondarily, matter oscillations have been studied extensively, in particular, with respect to oscillations of neutrinos from the sun and to oscillations of neutrinos produced in the atmosphere. In the sun, dramatic flavor change occurs when the electron density in the solar medium is the same scale as the vacuum parameters. Equation (1) shows the matter contribution as V_e, which depends directly on the density of electrons. In the absence of other effects, this scale

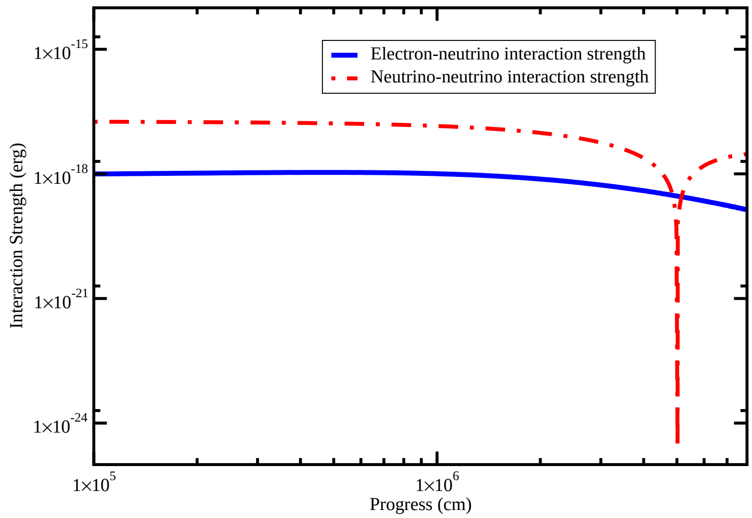

FIGURE 1. Both Hierarchies. The magnitudes of the interaction strengths for both hierarchies in units of erg. Until about 5×10^6 cm, the antineutrinos outnumber the antineutrinos and the interaction strength is negative. As the ejecta get further from the disk surface, they experience more of the neutrino emission, and the interaction strength becomes positive. A point has been added for the neutrino-neutrino interaction strength at $5.03\times10^6 cm$ to show that the neutrino density passes through zero.

matching can cause the cancellation of the diagonal of equation (1) and the off diagonal vacuum contributions yield large mixing. This is the well known Mikheev-Smirnov-Wolfenstein effect (MSW) [26, 27, 28]

Thirdly, an oscillation effect that has been mostly studied in the early universe and in the proto neutron star setting is one that arises from neutrino-neutrino scattering. Because of the large neutrino fluxes from an accretion disk from stellar collapse, the neutrino-neutrino interactions are non negligible. While our understanding of these effects is evolving, numerical and analytical works concerning proto neutron stars have found large scale neutrino oscillations when the neutrino-neutrino interactions become of the same scale as the vacuum interactions [10, 29]. In equation (1), the neutrino-neutrino interaction terms are V_{ν_e}, $V_{\bar{\nu_e}}$, V_{ν_μ}, and $V_{\bar{\nu_\mu}}$ on the diagonal and $V_{\nu_e\nu_\mu}$ and $V^*_{\nu_e\nu_\mu}$ on the off diagonal. These terms all depend directly upon the flavor dependent neutrino density. For example, V_{ν_e} is proportional to the density of electron neutrinos. In the absence of oscillation, it would be proportional to the density of all neutrinos. Depending on the neutrino hierarchy, these terms may cancel in part with the vacuum contribution.

Finally, in the accretion disk setting, another sort of scale matching and cancellation is possible. The neutrino-neutrino interaction may cancel the matter density, $\frac{Ve}{2}+\frac{V_{\nu_e}-V_{\bar{\nu_e}}+V_{\bar{\nu_\mu}}-V_{\nu_\mu}}{2}\sim 0$. In figure 1, we show the interaction strength due to the electrons and the interaction strength due to the neutrinos and antineutrinos together. The interaction strengths are presented as a function of the distance travelled by a chunk of ejected material as it leaves the disk surface from a point 30 km above the disk. When progress along the trajectory is 0 cm, which is above the disk, the neutrinos (antineutrinos) are taken to be in the electron flavor. In the beginning, the neutrino flux is primarily composed of electron antineutrinos, which give a negative contribution relative to the electron density. Further along the trajectory, the electron neutrino flux overtakes the antineutrino flux and the overall interaction strength from neutrino interactions becomes positive relative to the electron density. While the two interaction strengths have opposite signs, at about 5×10^6cm, the two may cancel. This cancellation can induce interesting oscillation physics, which we discuss in the Model and Calculations section.

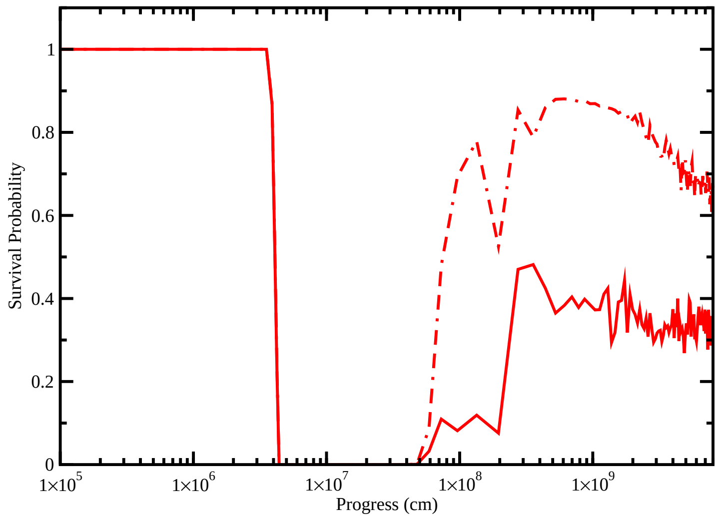

FIGURE 2. Normal Hierarchy. Survival probability of neutrinos (solid line) and antineutrinos (dot-double dashed line) as a function of progress along the trajectory.

MODEL AND CALCULATIONS

We calculate the neutrino oscillation pattern for a model of disks that arise from stellar collapse similar to those in [30, 31]. We focus on those disks where the accretion rates is such that only electron neutrinos and antineutrinos are trapped. Electron antineutrinos will be trapped in a region close to the disk center whereas the electron neutrino trapping surface will have a greater radius, but lower temperature. Our disks are geometrically flat, and have a single temperature throughout. They have holes in the centers, where no neutrinos or antineutrinos are emitted, with radius $R_0 = 3.2 \times 10^6$ cm. They have exterior radii $R_\nu = 1.5 \times 10^7$ cm and $R_{\bar{\nu}} = 10^7$ cm for the disks emitting electron neutrinos and electron antineutrinos respectively. The temperature of neutrinos emitted is $T_\nu = 3.2$ MeV and the temperature of emitted antineutrinos is $T_{\bar{\nu}} = 4.1$ MeV.

While the (anti)neutrino emission disk model is similar to model B in [24], we are using a different electron density. As discussed in the previous section, in well understood neutrino oscillation patterns, the electron density is crucial to understanding the MSW effect. In the accretion disk case, we fully expect the cancellation of the the electron interaction term with the neutrino interaction term to result in interesting oscillations. The size of the electron interaction strength determines when such oscillations begin. The larger the electron interaction, the earlier the onset will be. The location of the beginning of the oscillations can be particularly important when considering nucleosynthesis calculations as done in [24]. In this calculation, in particular we choose an electron density with $s/k_B = 80$, which is consistent with a wind outflow model as in [32]. Because this electron density is higher than the density chosen in [24], the onset of neutrino oscillations could appear sooner.

The calculations assumed that the neutrinos had a common history, an approximation known as the "single angle approximation." The three flavor neutrino oscillation parameters were mass-squared differences, $m_2^2 - m_1^2 = \delta m_{21}^2 = 7.59 \times 10^{-5}$ eV^2, $\left|m_3^2 - m_2^2\right| = \left|\delta m_{32}^2\right| = 2.43 \times 10^{-3}$ eV^2; and mixing angles, $\theta_{13} = 9^\circ$, $\theta_{12} = 34.4^\circ$ and $\theta_{32} = 45^\circ$. These choices are consistent with the current PDG values [33]. The results of the calculations are shown as the ratios of the electron neutrino capture rates. These are the survival probabilities for each energy, weighted to the energy squared. They are shown in figures 2 and 3 for the normal and inverted hierarchies respectively as a function of progress along the trajectory.

At the begininning of the trajectory, the electron interaction strength is large and the neutrino interaction strength is larger. The matrix of the right hand side of equation (1) is almost diagonal. As we would expect, little happens to the neutrinos and antineutrinos and they stay in the electron flavor. As the neutrinos progress, however, a large drop

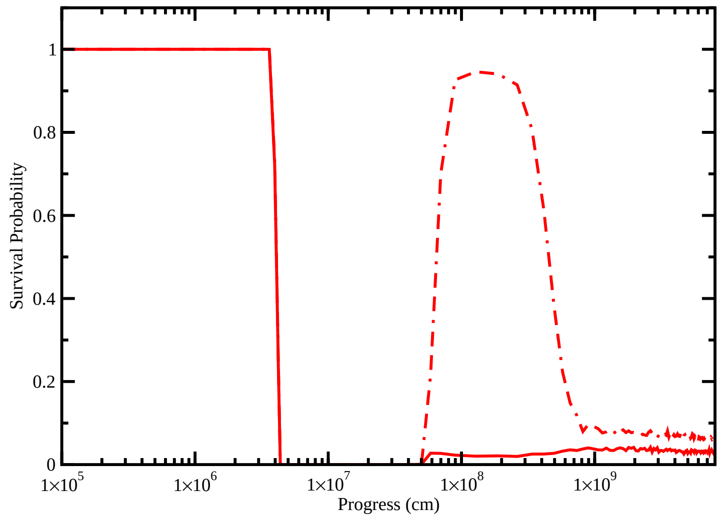

FIGURE 3. Inverted Hierarchy. Survival probability of neutrinos (solid line) and antineutrinos (dot-double dashed line) as a function of progress along the trajectory.

in the survival probability occurs at about 4×10^6 cm for both neutrinos and antineutrinos in both hierarchies. This is the point of cancellation between the electron interaction term and the neutrino interaction term. Because the rapid drop of the neutrino interaction term hastens the cancellation between the neutrino and electron interaction terms, the onset of oscillations due to the cancellation is in roughly the same place as in Model B of [24]. The cancellation is not possible in the supernova setting because the signs of the neutrino interaction strength are always positive relative to the electron interaction strength. This effect will not be seen there. The other features of the oscillation pattern are explainable in terms of the oscillations seen in the supernova case, which may be seen from a similar calculation appear in our paper, [24].

CONCLUSIONS

Neutrinos above accretion disks show compelling oscillation physics. The combination of the disk geometry with the ambient electron density enables cancellation between the electron interaction and neutrino interaction contributions to oscillation calculations. We have shown this cancellation is associated with large transitions of neutrino flavor. While disks may be home to several kinds of neutrino oscillation phenomena that have been seen elsewehere, this cancellation between electron interaction and neutrino interaction appears to be new.

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