Neutrino oscillations and supernovae

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Abstract

In a 1996 JRO Fellowship Research Proposal (Los Alamos), the author suggested that neutrino oscillations may provide a powerful indirect energy transport mechanism to supernovae explosions. The principal aim of this addendum is to present the relevant unedited text of Section 1 of that proposal. We then briefly remind, (a) of an early suggestion of Mazurek on vacuum neutrino oscillations and their relevance to supernovae explosion, and (b) Wolfenstein’s result on suppression of the effect by matter effects. We conclude that whether or not neutrino oscillations play a significant role in supernovae explosions shall depend if there are shells/regions of space in stellar collapse where matter effects play no essential role. Should such regions exist in actual astrophysical situations, the final outcome of neutrino oscillations on supernovae explosions shall depend, in part, on whether or not the LNSD signal is confirmed. Importantly, the reader is reminded that neutrino oscillations form a set of flavor-oscillation clocks and these clock suffer gravitational redshift which can be as large as 20 percent. This effect must be incorporated fully into any calculation of supernova explosion.

1 Section 1 of author’s 1996 J Robert Oppenheimer Fellowship Research Proposal: Unedited text

The following is an unedited text of Section 1 of author’s 1996 J Robert Oppenheimer Fellowship Research Proposal:¹

Neutrinos were introduced in physics by Pauli to save conservation of energy and momentum in the $\beta$-decay: Neutron $\rightarrow$ Proton + Electron + Anti-electron

¹ The reader is reminded that such proposals are written for a very broad readership, as the evaluators come not only from physics, but fields as far as biology, and other sciences. The proposal was submitted by M. B. Johnson in July 1996 in his “Nomination of Dharam Ahluwalia for Oppenheimer Fellowship.” The addendum title coincides with the title of Section 1 of the proposal.
Neutrino. All the planets and galaxies are embedded in a sea of neutrinos with a number density of roughly 100 neutrinos/cm$^3$. Our own Sun shines via thermonuclear processes that emit neutrinos in enormous number. Because of their weak interactions, neutrinos, unlike photons, can pass through extremely dense matter very efficiently. This fact makes neutrinos primary agents for energy transport in the dense matter associated with supernovae and neutron stars.

Since their initial experimental observation by Frederick Reines and C. L. Cowan, neutrinos are now known to exist in three types. These types are called “electron,” “muon,” and “tau” and are generically written as $\nu_e$, $\nu_\mu$, and $\nu_\tau$. A series of empirical anomalies indicates that neutrinos may not have a definite mass but, instead, be in a linear superposition of three different mass eigenstates. The mass differences in the underlying mass eigenstates would cause a neutrino of one type to “oscillate” to a neutrino of another type as may have been seen recently at the LSND neutrino oscillation experiment at LANL. The phenomenon of neutrino oscillations, if experimentally confirmed, will have profound consequences not only for nuclear and particle physics but also for astrophysics and cosmology.

I have already noted the neutrinos to be prime drivers of supernova explosions. The phenomenon of neutrino oscillations will alter the evolution of supernova explosion. The basic problem that still stands unsolved is a robust theory of supernova explosions. In the context of supernova explosions, and the problem of obtaining successful explosions, I now follow Colgate et al. [S. A. Colgate, M. Herant, and W. Benz, Phys. Rep. 227, 157 (1993)] and assume that the matter next to the neutron star is heated by neutrinos from the cooling neutron star. They note that in some models “this result in strong, large scale convective flows in the gravitational field of the neutron star that can drive successful, albeit weak, explosions.” I emphasize that all authors find that without “fine tuning” the explosions are weak and lack about five percent of the energy needed for an explosion. Qualitatively, this missing energy needed for a robust model of explosion may be provided if the length scales over which neutrino oscillations take place are of the same order of magnitude as the spatial extent of a neutron star and neutrino-sphere, because while

\[
L_{\nu_e} \approx L_{\bar{\nu}_e} \approx \text{few} \times 10^{52} \text{ ergs s}^{-1},
\]

the average energy of $\nu_e$ is about 10 MeV, the average energy of other neutrinos is higher by a factor of 2 for $\nu_\mu$ and $\bar{\nu}_\mu$, and by a factor of 3 for $\nu_\tau$, and $\bar{\nu}_\tau$.

Any oscillation between neutrinos of different flavors is, therefore, an indirect
energy transport mechanism towards the actively interacting $\nu_e$ and $\bar{\nu}_e$. Qualitatively this contributes in the direction of the robustness of the explosion. My recent work, with C. Burgard, on the solution of terrestrial neutrino anomalies provides precisely the neutrino oscillation parameters that yield the oscillation length scales of just the right order of magnitude for supernova physics (and in addition predict the observed solar neutrino deficit).

In order to make these qualitative arguments quantitative two additional physical processes affecting the above indicated vacuum neutrino oscillations must be incorporated: (a) The presence of large electron densities in astrophysical environment makes it necessary that relevant matter induced effects, suggested by Mikheyev, Smirnov and Wolfenstein, be considered, and (b) My work, with C. Burgard, on gravitationally induced neutrino oscillation phases also indicates that strong gravitational fields associated with neutron stars may introduce important modifications to neutrino oscillations, and hence to the suggested energy transport mechanism via neutrino oscillations. As part of my JRO studies I propose to implement the above outlined program quantitatively. My quantitative and qualitative studies so far give reasons to claim that there is every physical reason to believe that the “missing energy” in the non-robust models for supernova explosion, the anomaly in the observed deficit in the solar neutrino flux, the excess $\bar{\nu}_e$ events seen at LSND at Los Alamos, and the anomaly associated with atmospheric neutrinos, all arise from the same underlying new physics —the phenomenon of neutrino oscillations from one type to another. It is of profound physical importance to place these suspected physical connections on firm quantitative foundations.

2 Brief remarks

The above 1996 proposal was a logical continuation, and directly connected to, a work jointly done the same year with C. Burgard. It has been widely known informally, without a full access to its text. This addendum fills the gap of its availability.

While writing these remarks the author has learned that the effect of neutrino oscillations on supernovae explosions was first presented in a talk by Mazurek [1]. Soon afterward, Wolfenstein showed that for collapsing stellar cores, matter effects dramatically suppress neutrino oscillations [2], with the following one-line abstract, “It is shown that even if neutrino oscillations exist they are effectively inhibited from occurring in collapsing stars because of the high matter density.”

The suggestion that neutrino oscillations may play a significant role in supernovae explosions has been pursued vigorously, though often without acknowl-
edging the proposal of Sec. 1, or talk of Ref. [1].

The matter is far from settled, see, e.g. [3–7] and whether or not neutrino oscillations play a significant role in supernovae explosions shall depend if there are shells/regions of space in stellar collapse where matter effects [8,9] play no essential role. The spatial extent of these regions, we suspect, must be significantly smaller than neutron-star size. Should such regions exist in actual astrophysical situations, the final outcome of neutrino oscillations on supernovae explosions shall depend, in part, whether or not the LNSD signal is confirmed [10]. This is so because the LSND-suggested $\Delta m^2$ alone gives smallest, by about three orders of magnitude (as compared with the solar and atmospheric data [11–13]), required vacuum-oscillation length. Assuming a $\Delta m^2 \approx 0.4 \text{ eV}^2$ – as discussed on numerous occasions as early as 1994 at Los Alamos by one of us, $^2$ and noted in Ref. [16] – the obtained length ranges from about 10 meters for a 1 MeV neutrino, to 300 meters for a 25 MeV neutrino.

Importantly, it is to be noted that neutrino oscillations form a set of flavor-oscillation clocks and these clock suffer gravitational redshift which can be in the neighborhood 20 percent. This effect must be incorporated fully into any calculation of supernova explosion. References [17–22] shed further light on Ref. [16] and deal with impact of gravity on neutrino oscillations.

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