Collective neutrino oscillations in supernovae: Matter suppression during the accretion phase

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We carry out a detailed analysis of the supernova (SN) neutrino flavor evolution during the accretion phase (at post-bounce times $t_{pb} \leq 500$ ms), characterizing the SN ν signal by recent hydrodynamical simulations. We find that trajectory-dependent "multi-angle" effects, associated with the dense ordinary matter suppress collective oscillations, that would have been induced by $\nu - \nu$ interactions in the deepest SN regions. The matter suppression implies that neutrino oscillations will start outside the neutrino decoupling region and therefore will have a negligible impact on the neutrino heating and the explosion dynamics. Furthermore, the possible detection of the next galactic SN neutrino signal from the accretion phase, based on the usual Mikheyev-Smirnov-Wolfenstein effect in the SN mantle and Earth matter effects, can reveal the neutrino mass hierarchy in the likely case that the mixing angle θ_{13} is not very small.

1 Introduction

The total energy emitted in neutrinos (ν) and antineutrinos ($\bar{\nu}$) during a supernova (SN) explosion is of the order of several 10^{53} erg, making a stellar collapse the most powerful neutrino source in the Universe. The huge neutrino fluxes emitted from such an event represent a crucial tool to obtain information about the ν mixing parameters and to understand the dynamics of the exploding stellar core. In particular, one expects a strong sensitivity of the SN ν signal on the flavor conversions occurring in the stellar envelope. In this context, it has been recently realized that the description of neutrino flavor evolution in supernovae based on the only Mikheyev-Smirnov-Wolfenstein (MSW) effect with the ordinary matter is incomplete since SN neutrinos not only interact with the stellar medium but also with the other ν's and $\bar{\nu}$'s. It has been shown that $\nu - \nu$ interactions can give rise to collective ν flavor conversions occurring between the neutrino sphere ($r \sim 10 - 100$ km) and the MSW region ($r \sim 10^3 - 10^5$ km). The most important observational consequence of these collective oscillations would be a swap of the ν_e and $\bar{\nu}_e$ spectra with the non-electron ν_x and $\bar{\nu}_x$ spectra in certain energy ranges [1].

The development of these self-induced ν transformations crucially depends on the primary SN ν spectra. In this context, the post-bounce accretion phase of a core-collapse SN, lasting up to several hundreds of milliseconds for iron-core progenitors, might seem to offer the best opportunity to detect signatures of collective ν flavor oscillations. Indeed, the absolute ν fluxes during this phase are large with significant spectral differences between the ν species, and a flux
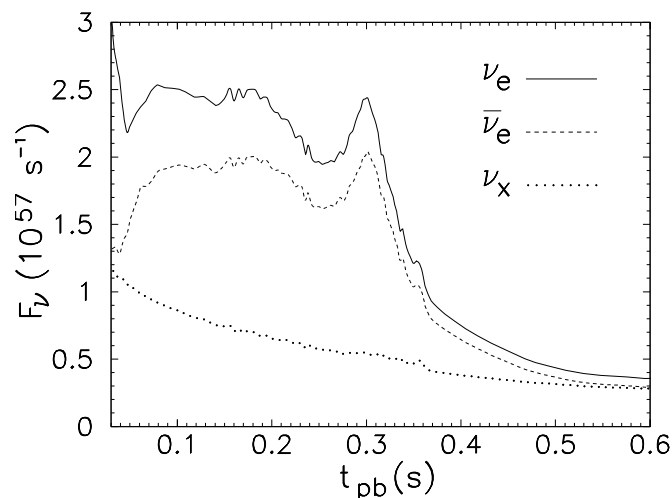
Figure 1: ν number fluxes during the accretion phase for a SN model with 10.8 $M_\odot$ progenitor mass from the Basel simulations [3].

order $F_{\nu_e} > F_{\overline{\nu}_e} \gg F_{\nu_x}$. However, the description of flavor conversions triggered by neutrino self-interactions is only in part true. In fact, as recently pointed out in [2], when the electron density n_e is not negligible with respect to the neutrino density n_ν, the large phase dispersion induced by the matter potential for ν's traveling on different trajectories will partially or totally suppress the collective oscillations through peculiar "multi-angle" effects.

Driven by this insight, we have performed a detailed study of the SN ν flavor evolution during the accretion phase, characterizing the ν signal and the matter density profiles by means of recent neutrino radiation hydrodynamics simulations [3]. Using this input, we find that the "multi-angle" effects, associated with the dense ordinary matter, suppress collective oscillations during the accretion phase. In particular, both the situations of complete (when $n_e \gg n_\nu$) or partial (when $n_e \gtrsim n_\nu$) matter suppression can be realized. In the following we will present these results and their consequences. This paper is based on our works [4, 5], to which we address the interested reader for further details.

2   Setup of the flavor evolution

We take as benchmark for the ν signal and for the matter density profile the results of the recent long-term SN simulations performed by the Basel group [3]. In Fig. 1 we show the evolution of the ν number fluxes F_{ν_α} for the different neutrino flavors ν_α up to 0.6 seconds after core bounce, for a 10.8 $M_\odot$ iron-core progenitor model.

Our description of the ν flavor conversions is based on a two-flavor scenario, driven by the atmospheric mass-square difference $\Delta m^2_{\text{atm}} \simeq 2.6 \times 10^{-3}$ eV^2 and by a small (matter suppressed) in-medium mixing $\theta_{\text{eff}} = 10^{-3}$. We work in the inverted ν mass hierarchy ($\Delta m^2_{\text{atm}} = m^2_3 - m^2_{1,2} < 0$) and schematically we assume all the ν's to be emitted with the same energy $E = 15$ MeV. The impact of the non-isotropic nature of the ν emission on the flavor conversions is taken into account by "multi-angle" simulations, where one follows a large number $[\mathcal{O}(10^3)]$
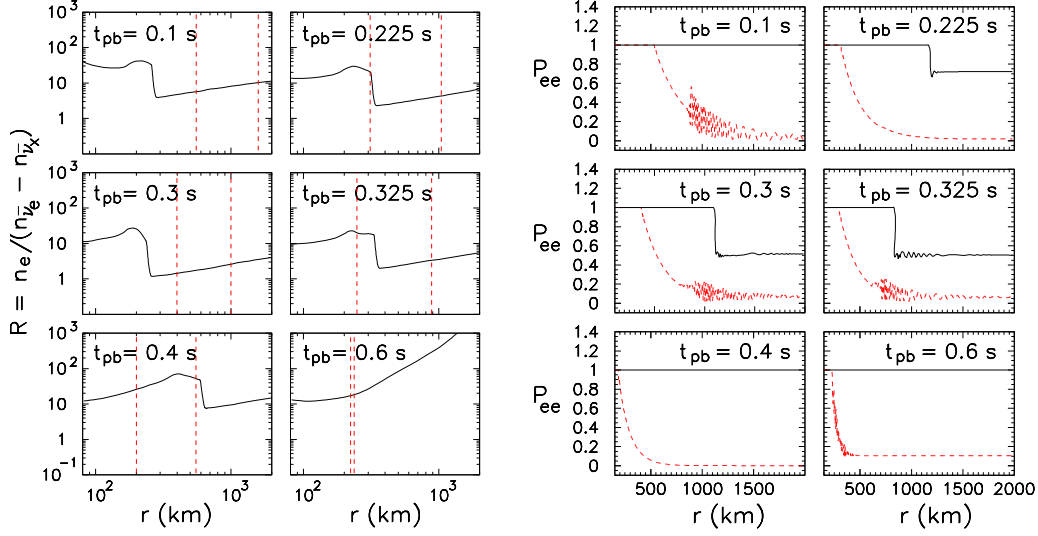
Figure 2: (color online) *Left panel*: Radial evolution of the ratio R between electron and neutrino densities at different post-bounce times. The two dashed vertical strips delimit the range where collective oscillations would arise in absence of matter effects. *Right panel*: Radial evolution of the survival probability P_{ee} for electron antineutrinos at different post-bounce times for the multi-angle evolution in presence of matter effects (continuous curve) and for $n_e = 0$ (dashed curve).

of intersecting ν trajectories.

The strength of the ν–ν interaction is given by $\mu_r = \sqrt{2} G_F [n_{\overline{\nu}_e}(r) - n_{\overline{\nu}_x}(r)]$ [6], where $n_{\nu_\alpha}(r) = F_{\nu_\alpha}/4\pi r^2$ is the number density of the species ν_α. The ν–ν potential is normalized at the neutrinosphere $[r_\nu \sim \mathcal{O}(10^2)$ km], where ν's are assumed to be isotropically emitted [6]. The matter potential is represented by $\lambda_r = \sqrt{2} G_F n_e(r)$, encoding the net electron density, $n_e \equiv n_{e^-} - n_{e^+}$.

3 Matter versus neutrino potential: analysis and results

In order to compare the strength of the matter and the neutrino potential, we show in Fig. 2 ratio $R = n_e/(n_{\overline{\nu}_e} - n_{\overline{\nu}_x})$ at selected post-bounce times (left panel). We realize that n_e is always larger than or comparable to $n_{\overline{\nu}_e} - n_{\overline{\nu}_x}$, suggesting that matter effects cannot be ignored during the accretion phase. Depending on the strength of the matter density, the matter suppression can be total, when $n_e \gg n_\nu$, or partial when the matter dominance is less pronounced. Finally, when $n_e \geq n_\nu$ the interference of the two comparable potentials leads to flavor equilibrium with a complete mixture of electron and non-electron species [2].

To validate these expectations, we show in the right panel of Fig. 2 the radial evolution of the $\bar{\nu}_e$ survival probability P_{ee} for the same post-bounce times used in the left panel. As predicted, we find that matter strongly suppresses the development of the self-induced flavor transformations. In particular, at $t_{\mathrm{pb}} = 0.1, 0.4, 0.6$ s, when $n_e \gg n_\nu$, the flavor conversions are completely blocked ($P_{ee} = 1$). Conversely, at $t_{\mathrm{pb}} = 0.225$ s, when $n_e \simeq 2n_\nu$ in the conversions

region, the matter suppression is only partial giving a final $P_{ee} \simeq 0.75$. Finally at $t_{\mathrm{pb}} = 0.3, 0.325$ s, when $n_e \geq n_\nu$, matter effects produce a complete flavor mixture ($P_{ee} = 1/2$). This behavior suggests a time-dependent pattern for the ν conversions, i.e. complete-partial-complete suppression. For comparison, we also show the results in the case of $n_e = 0$ (light curves). One realizes that the difference with respect to the previous cases is striking.

4 Conclusions

Simulations of core-collapse SNe show that the matter density in the deepest stellar regions is large during the accretion phase before the onset the an explosion. This implies that self-induced neutrino flavor transformations are affected by the high matter density, through trajectory-dependent multi-angle effects [2]. In order to characterize the SN ν flavor evolution in this case, we performed a dedicated study, taking as benchmark for the SN neutrino emissivity and the matter profiles the results from the recent long-term core-collapse SN simulations from Ref. [3].

We find that the electron density n_e is never negligible in comparison to the neutrino density n_ν during the accretion phase. Contrarily to what shown in previous studies, based on the only ν-ν interaction effects, we find that the presence of a dominant matter term inhibits the development of collective flavor conversions. The matter suppression ranges from complete to partial, producing in principle time-dependent features. In particular, when it is complete (for post-bounce times $t_{\mathrm{pb}} \leq 0.2$ s in iron-core SNe) the ν signal will be processed only by the usual MSW effect in the SN mantle and Earth matter effects. This was the usual description before the inclusion of collective phenomena.

This *déjà vu* would reopen the possibility, prevented by self-induced effects, to reveal the neutrino mass hierarchy through the Earth matter effects on the next galactic SN neutrino burst, in the case θ_{13} is not very small. The matter suppression also implies that neutrino oscillations will start outside the neutrino decoupling region and therefore will have a negligible impact on the neutrino heating and the explosion dynamics.

Acknowledgments

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