Neutrino Oscillations in Core-Collapse Supernovae

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Abstract

Aiming to calculate the neutrino oscillations in core-collapse supernovae theoretically. Neutrinos are one of the key players in core-collapse supernovae.They carry most of the energy relieved by the gravitational collapse of massive star cores. There are three types of neutrinos. ν_e,ν_μ and ν_τ.These are the partners of the corresponding charged leptons; electron,muon and tauon respectively and produced via charged current interactions such as β-decay and decay of muons and tauons. The lepton mixing result in that, for example, a ν_e which is produced by β-decay is linear combination of some mass eigenstate ν_i. More generally neutrinos are always produced and detected in flavor eigenstates which are not eigenstates of the propagation hamiltonian. This mismatch leads to neutrino oscillation. My main focus is for when the neutrino oscillations are modified by the presence of neutrinos themselves.In this case it becomes nonlinear which its calculation is more difficult than the ordinary oscillations. In this program I will present the theoretical study of the neutrinos in constant and varying densities. I also present my recent collaboration with my colleague for studying the neutrino oscillation for three progenitors.

1 Introduction

Core-collapse supernova signify the death of massive stars heavier than 8 solar mass and the birth of proto-neutron stars(Meng-Ru Wu et al.2014). They are energetic deaths of massive stars at the end of their lives. In spite of the intensive studies over the last half century, the mechanism is still ambiguous. The research of core-collapse supernova is very important for a couple of reasons: firstly, its understanding fills the last piece of stellar evolution theory. Secondly, core-collapse supernova are the main agents in cosmic synthesis of heavy nuclei;they emit copious neutrinos as well as gravitational waves, hence being one of the chief targets for nascent neutrino and gravitational wave astronomies.

Neutrinos are supposed to be key player in Core-collapse supernovae. They carry most of the energy relieved by the gravitational collapse of massive star cores. If only one e percent of their energy is transferred to stellar matter, core-collapse supernova will be produced.

The problem with the current supernova theory is: this has not been achieved convincingly in the most sophisticated numerical simulations so far. The purpose of my research is to study neutrino oscillations in core-collapse supernovae theoretically. Neutrinos are aslo important observationally. They will provide us with invaluable information on the properties of nuclear matter at high densities, which would not be accessible otherwise.

Neutrinos also are useful to unveil the progenitor of core-collapse supernovae, since neutrino emissions are already started before core-collapse. Matter-modified neutrino oscillations or the MSW (Mikheyev-smirnov-Wolfstein) effect are expected to occur here and hence should be taken into account in the interpretation of observed signals. I also contributed in another research which we could obtain successful results and we could publish them recently.

2 Methods

The theoretical study of neutrino oscillations has been done by many authors around the world. It is now almost established that neutrinos have tiny but non-vanishing masses. Like quarks neutrinos have three generations and are mixed among them. This fact, although posing another complexity in core-collapse supernovae, may have an important consequence for the mechanism of core-collapse supernovae. In fact, it is well known that mu- and tau neutrinos have higher energies than electron neutrinos. If the former is converted to the latter and then absorbed by matter, more energy is transferred and may induce successful explosions. The interesting thing is that the neutrino oscillations are modified by the presence of the neutrino themselves; then the problem becomes nonlinear and far more difficult than the oridnary oscillation.

as a result, full understanding of this so-called collective oscillations has not been achieved.

Our idea in tackling the combined nonlinear problem is to apply the linear stability analysis to the results of the detailed numerical simulations without neutrino oscillations and see if the so-called collective neutrino oscillations occur at some point in the evolution of the core-collapse.

The neutrino oscillations in vacuum:

$$i\frac{\partial}{\partial z}\Psi_E^{(f)} = \frac{UM^2U^\dagger}{2E}\Psi_E^{(f)} \tag{1}$$

where the mixing matrix for two flavors is given as:

$$\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{2}$$

and the mixing matrix for three flavor case is given as:

$$\begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -C_{23}S_{12} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & C_{13}S_{23} \\ S_{12}S_{23} - S_{13}e^{i\delta} & -C_{12}S_{23} - C_{23}S_{12}S_{13}e^{i\delta} & C_{13}C_{23} \end{bmatrix} \tag{3}$$

and for oscillation in matter :

$$i\frac{\partial}{\partial z}\Psi_E^{(f)} = \left(A + \frac{UM^2U^\dagger}{2E}\right)\Psi_E^{(f)} \tag{4}$$

where, A is the mass matrix representing the contribution from interaction with matter. Neglecting the background neutrino, we have:

$$A = \frac{G_F n_B}{\sqrt{2}}\begin{bmatrix} 3Y_e & 0 & 0 \\ 0 & Y_e - 1 & 0 \\ 0 & 0 & Y_e - 1 \end{bmatrix} \tag{5}$$

here we used,$Y_n = 1 - Y_p = 1 - Y_e$ but the contribution from neutrons is not important for neutrino oscillation because it is proportional to identity matrix. This reflects the fact that the interactions with neutrons is via the neutral-current interaction which occurs equally for all flavors.

and the collective neutrino oscillation in which A depends on neutrino densities is the main goal of my research.

as far as we know, neutrino and anti-neutrino densities near the neutrino sphere are extremely high ($10^{30-35} cm\ per\ cm^3$),which make the neutrino-neutrino interactions significant. such a dense gas of neutrinos and anti-neutrinos is coupled to itself and making the flavor evolution non-linear. the flavor off diagonal terms can be sizeable and significant flavor conversion is possible. Dense gas of neutrinos display collective flavor conversion i.e. neutrinos of all energies oscillate together through synchronized and/or bipolar oscillations which will be studied during my research in details.

3 Discussion

As mentioned above that the neutrinos can be also useful to present the progenitors of the core-collapse supernova as the neutrino emissions already started before the core-collapse. MSW effect has been expected to occur here. I contributed one of my colleagues in her research and studied neutrino oscillations for three different progenitors (8.4 , 12 and 15 solar mass). In this work I calculated the density scale height H_ρ and the mixing lengths l_m for three progenitors. I calculated the radii of the resonance points to show whether the neutrino oscillation will be in adiabatic regime or not.

Neutrino oscillation will occur in adiabatic regime if $l_m \ll H_\rho$.

In the upper panels the density distribution for three progenitors has been sketched.

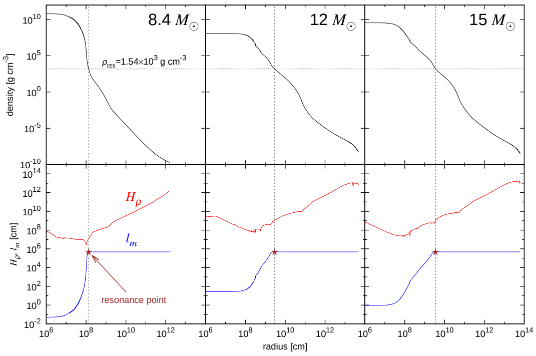

図 1: Inverted mass heirarchy is suggested and resonance points are shown. The radii of resonance points for 8.4,12and15$M_\odot$ are:1.3×10^8,$2.95\times10^9$and $3.53\times10^9 cm$ respectively.

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