Neutrinos from supernovae

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Abstract. The physics of supernova neutrinos continues to be a puzzle. Insight into the nature of collective oscillations, that were obtained over the past decade, are slowly beginning to reveal a rich phenomenology. One of major issues is the role of symmetry breaking, be it in spatial homogeneity or temporal stationarity. We reported some new results in this specific area and reviewed the progress in the field of supernova neutrinos, in general.

1. Recent developments in supernova neutrinos

Stars with masses more than $\sim 8 M_{\odot}$, that run out of fusion-fuel towards the end of their lives, collapse under their own gravity. This collapse is hydrodynamically turned outwards into a supernova explosion that is aided and accompanied by neutrino emission. Neutrinos in the energy range 1-100 MeV, that were thermalized in the protoneutron star, are emitted over ∼10 s. As these neutrinos travel through the exploding star, the three neutrino flavors oscillate and convert into each other, leading to an energy-dependent redistribution of the fluxes.

The output neutrino flux is observable with existing experiments if the SN occurs in/near the Milky Way. SN1987A was employed for obtaining stringent bounds on new physics, but an observation with present/proposed detectors promises a qualitatively superior high-statistics dataset. The expected rate for Galactic supernovae is 1-3 per century, making a supernova neutrino observation quite plausible in our lifetimes. The basic strategy of supernova neutrino physics is therefore to predict the expected neutrino signals at various detectors, for plausible choices of initial neutrino fluxes and astrophysical parameters, and to compare with a future observation [1].

One of the key theoretical challenges in being able to make flux predictions is to understand neutrino-neutrino interactions that lead to "collective" flavor conversions. Collective flavor oscillations of neutrinos streaming-off the core of a supernova are a rich and complex phenomenon [2, 3], and drastically changes the traditional paradigm of neutrino oscillations in a passive medium. Major progress has been made in the last ten years and we now know that neutrino-neutrino interactions lead to highly correlated oscillations and many unexpected flavor conversion effects. However, the problem remains extremely complex and challenging in its generality.

In order to reduce the complexity of this problem, symmetries in the flavor evolution have typically been assumed. For neutrinos in a SN environment, a steady-state solution is assumed. Moreover, under the assumption of spherically symmetric neutrino emission, the dynamics is reduced to be only along the radius. These time and space symmetry assumptions have been recently criticized because flavor instabilities may grow when initial symmetries aren't exact [4].

Self-interacting neutrinos can spontaneously break the rotational symmetry in space. In fact, even tiny inhomogeneities could lead to new flavor instabilities, developing even at large neutrino densities, where oscillations are otherwise expected to be suppressed due to synchronization. However, large neutrino densities in a supernova are typically accompanied by a large matter density, which produces the known "multi-angle matter effects" [5] that suppresses these low-radii small-scale instabilities [6]. A key unanswered question is "Is this steady-state solution stable?" In this context, we reported some new results on "What is the role of temporal stationarity and how can instabilities arise when such stationarity is not exact?" [7, 8].

The impact of ordinary matter, via the well-known Mikheev-Smirnov-Wolfenstein (MSW) effect, also poses interesting challenges some of which haven't yet been fully addressed. Although adiabatic and non-adiabatic MSW transitions, modifications due to shockwave propagation, and earth effects are theoretically understood, the astrophysical parameters that determine the magnitude of these effects are still unknown. For more complex issues, e.g., role of turbulence in the stellar media, and strong asymmetries in the explosion, theoretical work is still in progress. The next supernova will be useful in providing further guidance.

The study of supernova neutrinos is of crucial importance to existing and upcoming neutrino detectors. Existing experiments such as Super-K, KamLAND, Borexino, LVD and IceCube are sensitive to Galactic supernovae. Gd doping for Super-K is now approved and it is very likely that the diffuse supernova neutrino background will be soon detected. It is likely that JUNO [9], a large scintillator detector, will be built in China. Similarly, there are strong proposal by Japan to construct Hyper-K, a megaton scale water Cherenkov detector. The US effort seems to be towards a large liquid Argon detector, e.g., DUNE [10], and the European community has adopted a three pronged approach in the LAGUNA project – evaluating site possibilities and a choice of detector technologies [11]. All these experiments will be capable of detecting supernova neutrinos and promise a bonanza of new data for neutrino astrophysics. Some recent and ongoing work has focussed on specific detectors and estimating signal yields and physics output for benchmark astrophysical and physics scenarios.

Neutrinos also have far-reaching consequences for supernova theory [12]. In particular, neutrinos are thought to be essential for re-energizing supernova explosions by determining how energy is transferred efficiently to the stellar matter. This is a problem that has occupied astrophysicists for over a half a century now and we may finally find the missing piece of the supernova puzzle in neutrino oscillations. Collective oscillations may hold a key to successful explosions [13]. I anticipate that neutrino physics will have very important things to say about this issue in the coming 2-3 years.

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