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Review

Physics opportunities with supernova neutrinos

Georg G. Raffelt

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80802 München, Germany

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ABSTRACT

The high-statistics neutrino signal from the next nearby supernova (SN) would provide a bonanza of astrophysical and particle-physics information. In particular, there are two new developments in this field: (i) The SASI instability can imprint potentially detectable short-time variations on the neutrino signal. (ii) Collective neutrino oscillations strongly modify the previous paradigm of SN neutrino oscillations with potentially detectable consequences.

1. Introduction

The neutrino observation of SN 1987A in the Large Magellanic Cloud with a total of about two dozen events remains the only detected astrophysical neutrino source other than the Sun. Therefore, observing a SN "neutrino light curve" with high statistics is among the top science goals of neutrino astronomy worldwide. The flagship detectors are Super-Kamiokande and IceCube that would see a significant SN burst out to about 100 kpc and thus cover our galaxy and its satellites, whereas a future megatonne class detector reaches as far as the Andromeda galaxy at a distance of 780 kpc. In future, large-scale scintillator or liquid-Argon detectors may also play an important role [1,2].

Unfortunately, galactic SNe are rare, perhaps a few per century [3], although it has been noted that the number of observed SNe over the past ten years in galaxies out to 10 Mpc has been almost twice the expected rate [4]. In any case, the neutrino signal from the next nearby SN is probably a once-in-a-lifetime opportunity that must not be missed. Almost 30 years of nearly continuous neutrino sky coverage since 30 June 1980 when the Baksan Scintillator Telescope (BST) took up operation proved that a long-term neutrino watch is realistic. It is likely to continue for at least several decades, so chances are that a high-statistics SN neutrino signal will be observed eventually and indeed could happen any day. In that case the Supernova Early Warning System (SNEWS), a network of neutrino detectors, issues a real-time alert to the neutrino and astronomy communities [5].

What can we learn from a high-statistics SN neutrino observation? Forecasting all possible scenarios would be both impossible and moot. Rather, we will focus on a few generic issues. In Section 2 we will review some of the lessons from SN neutrinos as astrophysical messengers. In Section 3 we turn to some recent developments in the area of SN neutrino oscillations, a field that is in a state of flux since the importance of collective oscillations was recognized a few years ago. Section 4 is given over to a summary and conclusions.

2. Astrophysical lessons from a SN neutrino observation

2.1. Early warning, distance, direction, and precision bounce time

Most galactic SNe are optically obscured, explaining the small number of historical SNe (about five during the past millenium), so it is interesting that it can be located by its neutrinos alone [6,7]. The best pointing capability is provided

E-mail address: raffelt@mppmu.mpg.de.

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by $\nu + e \rightarrow \nu + e$ scattering in Super-Kamiokande with an accuracy of about 8° (95% CL half-cone opening angle). If neutron tagging becomes possible by adding gadolinium [8], the accuracy increases to about 3°.

The distance of SN 1987A could be directly determined with light echoes from its inner ring. If the next galactic SN is obscured one may have to rely on neutrinos to estimate its distance. The total emitted energy and the fraction visible as $\bar{\nu}_e$ depends on many uncertainties, so it is unlikely that the distance could be estimated to better than a factor of two. The prompt ν_e burst, on the other hand, comes close to being a standard candle [9], but the world lacks a big ν_e detector. In a large liquid-Argon TPC the charged-current absorption $\nu_e + ^{40}\mathrm{Ar} \rightarrow ^{40}\mathrm{K} + e^-$ would provide an exquisite ν_e signal [10]. In a megatonne water-Cherenkov detector with neutron tagging, the signal from νe scattering could be isolated and a distance determination within 5%–10% may become possible [9].

Recently a strong case was made for the importance of precise coincidence measurements between gravitational wave and neutrino signals from SN core bounce [11]. At a pessimistic SN distance of 20 kpc, both Super-Kamiokande and IceCube can time the bounce to within a few tens of milliseconds, comparable to the expected duration of the gravitational wave burst [11,12]. The millisecond precision that can be achieved for a closer SN depends on the flavor oscillation scenario to relate the onset of the neutrino signal to the true bounce time.

Besides the obvious astrophysical importance of such a coincidence measurement, one could test the weak equivalence principle. Both neutrinos and gravitational waves should suffer the same Shapiro time delay in the gravitational potential of the galaxy that was a few months for SN 1987A in the Large Magellanic Cloud. The coincidence of the neutrino burst with the rise of the light curve within a few hours proved an equal Shapiro delay to within about 10^{-3} for photons and neutrinos [13, 14]. A millisecond-scale coincidence between neutrinos and gravitational waves would extend and refine this test, in detail depending on the location of the SN.

A long time ago it was suggested that one could use the neutrino-gravitational wave coincidence as a means to measure or constrain neutrino masses [15]. However, the cosmological neutrino mass limit of approximately 0.2 eV (0.62 eV at 95% CL for the sum of all three flavors [16]) implies that time-of-flight effects caused by a non-zero mass can be safely ignored for all practical intents and purposes.

2.2. Neutrino spectrum

The SN 1987A neutrino observations provided a unique confirmation of the overall picture of the core-collapse phenomenon. (For a recent review of SN theory see Janka et al. 2006 [17].) In detail, however, the observed $\bar{\nu}_e$ energies do not agree well with each other or with expectations. A much better fit is obtained with a two-component model. A much better fit is obtained with a two-component model with parameters optimized to reproduce typical predictions [18]. The standard delayed explosion scenario is without obvious alternative and seems to work well for low-mass progenitor stars where even spherically symmetric numerical models explode [19]. On the other hand, higher-mass progenitor stars show an extended phase of accretion and convective motions. In addition, the Standing Accretion Shock Instability (SASI) mode develops, a coherent oscillation of the proto neutron star against the cavity formed by the standing shock wave [20–24]. On average, the shock-wave radius is pushed to larger radii and allows the infalling material to be exposed to the neutrino flux longer and absorb more energy [22], although it remains unclear whether additional physics ingredients are required. Three-dimensional models with full-fledged neutrino transport are not yet available. Moreover, the core-collapse and explosion phenomenon is not necessarily universal and may well depend, for example, on the progenitor mass, amount of accretion, or speed of rotation. Therefore, the neutrino flux spectra emitted by different SNe presumably vary from case to case.

2.3. Signal duration

The signal duration of the SN 1987A burst agrees well with expectations. This observation is the basis for perhaps the most useful particle-physics lesson from SN 1987A: apparently there was no other energy-loss channel but the ordinary neutrinos. This "energy-loss argument" has been applied to a large number of cases, notably axions, Majorons, right-handed neutrinos, Kaluza–Klein gravitons and unparticles, often providing the most restrictive limits on the underlying particle-physics model [25–31]. Far-reaching conclusions about fundamental physics are here based on a sparse sample of data. Even a relatively low-statistics observation would be enough to remove any lingering doubt if these energy-loss limits are actually correct. Beyond a general confirmation, a high-statistics observation would not improve such limits very much because their uncertainties are typically dominated by physics in the SN core. This includes uncertainties about the temperature, density and composition of the medium as well as uncertainties of how to calculate interaction and emission rates in a nuclear medium.

2.4. High-statistics light curve

If one were to observe a high-statistics neutrino light curve, crucial details of the core-collapse paradigm could be tested. In particular, one could separate the early accretion phase from the later Kelvin–Helmholtz cooling phase after the explosion has been launched. Besides Super-Kamiokande, the IceCube detector would be well suited to this task even though it does not provide spectral information, but a high-statistics "bolometric" neutrino light curve that reflects the time-structure of the burst with high significance.

A detailed cooling profile would allow one to test the theory behind neutrino transport in a hot nuclear medium. Moreover, one may be able to detect short-term time variations that are caused by the large-scale convection pattern and the SASI mode during the accretion phase [23]. A sudden termination would reveal late black-hole formation. Of course, there could be completely unexpected features. It is noteworthy that the cosmological neutrino mass limits are now so restrictive that one can resolve millisecond structures in the neutrino light curve without wash-out by time-of-flight dispersion.

3. Neutrino flavor oscillations

3.1. Flavor dependence of SN neutrino fluxes

Over the past decade, neutrino flavor oscillations have been firmly established and one naturally wonders if flavor conversions play some role in SNe. Perhaps the most important flavor-dependent feature of SN physics is the large fraction of trapped e-lepton number after collapse and concomitant chemical potentials for electrons and ν_e. However, by the same token there are huge matter effects, suppressing flavor conversions in the core. Therefore, flavor oscillations influence neutrinos only when they stream from the core.

Nontrivial oscillation effects require flavor-dependent fluxes. Neutrino energies are far below the μ and τ mass thresholds. Therefore, ν_μ, $\bar\nu_\mu$, ν_τ, and $\bar\nu_\tau$, collectively denoted as ν_x, have only neutral-current interactions and their flux spectra emerging from the SN and their detection cross sections are almost the same. On the other hand, ν_e and $\bar\nu_e$ have charged-current interactions, notably with protons, neutrons and nuclei with different abundances, so we finally need to distinguish between the three species ν_e, $\bar\nu_e$ and ν_x. Oscillation effects can be summarized in terms of the energy-dependent ν_e survival probability $p(E)$ that gives us the ν_e flux at the detector as

$$F_{\nu_e}(E) = p(E)F^0_{\nu_e}(E) + [1 - p(E)]F^0_{\nu_x}(E), \tag{1}$$

where the superscript zero denotes the primary fluxes. An analogous expression pertains to $\bar\nu_e$ with the survival probability $\bar p(E)$.

The largest difference among the flavor fluxes arises during the first 10–20 ms after bounce when the outer layers of the collapsed core deleptonize, leading to the prompt ν_e burst [9]. Oscillation effects are strong during this phase, but they are hard to measure because existing and near-future detectors primarily see inverse beta decay $\bar\nu_e + p \to n + e^+$. In Super-Kamiokande, the prompt ν_e burst from a SN at 10 kpc would generate of order 10 events from ν_e scattering, so the burst could be just barely detected. In a megatonne water-Cherenkov detector with neutron tagging, the ν_e burst would be a useful tool both for studying flavor oscillations and determining the SN distance [9]. Likewise, a large liquid-Argon TPC would be a powerful ν_e detector [10].

When the deleptonization burst reaches its peak, the $\bar\nu_e$ and ν_x luminosities turn on. During the subsequent accretion phase (that can be very short for low-mass progenitors) one finds approximately $L_{\nu_x} < L_{\bar\nu_e} \approx L_{\nu_e}$ and $\langle E_{\nu_x}\rangle > \langle E_{\bar\nu_e}\rangle > \langle E_{\nu_e}\rangle$. When the accretion phase is pronounced (for the more massive progenitor mass iron core SNe), L_{ν_x} can be a factor of two smaller than $L_{\bar\nu_e} \approx L_{\nu_e}$ and the hierarchy of energies is significant [32–34]. During this phase one expects large and potentially measurable flavor oscillation effects.

When the shock wave has taken off, the star contracts and the cooling phase begins. All neutrino flavors now originate close to the neutron star surface. The material is very neutron rich, suppressing charged-current reactions for $\bar\nu_e$, so one expects that the luminosities and spectra of $\bar\nu_e$ and ν_x become quite similar and it will be much harder to see flavor oscillation effects in the dominant $\bar\nu_e$ detection channel. The relatively small differences between the flavor fluxes and spectra depend on many details of neutrino transport (the density and temperature profile as well as the treatment of the interaction rates) [32]. Recent long-term cooling calculations [34] find almost perfect luminosity equipartition and a small but non-negligible hierarchy of energies. However, these simulations did not necessarily use a complete treatment of the neutrino interaction rates, so this need not be the last word about the detailed cooling phase flavor fluxes and spectra. There is no question that during the cooling phase the SN core is very roughly a blackbody source for neutrinos of all flavors and that flavor-dependent flux and spectral differences are small, but perhaps can be large enough to cause observable effects in a high-statistics observation.

3.2. MSW oscillations and other matter effects

Neutrinos streaming away from a SN core pass through the mantle and envelope of the progenitor star and encounter a vast range of matter densities, implying two MSW resonances. One of them corresponds to the "atmospheric mass difference" (H-resonance), the other, at lower density (L-resonance) to the "solar mass difference". Of particular interest is the MSW effect at the H-resonance driven by the unknown mixing angle Θ_{13}. This resonance occurs in the neutrino sector for the normal mass hierarchy (NH) and among anti-neutrinos for the inverted hierarchy (IH). It is adiabatic for $\sin^2\Theta_{13} \gtrsim 10^{-3}$ and non-adiabatic for $\sin^2\Theta_{13} \lesssim 10^{-5}$. Therefore, the neutrino burst is, in principle, sensitive to Θ_{13} and the mass hierarchy [35,36].

It is straightforward to evaluate the ν_e and $\bar{\nu}_e$ survival probabilities, allowing one to calculate the fluxes emerging from the SN according to Eq. (1). However, these simple "flavor transfer functions" of the SN mantle and envelope usually get modified in several ways. On the detection side, regeneration effects in the Earth can be relevant if the SN is observed in a position "shadowed" by the Earth. Earth effects result in a characteristic energy-dependent modulation of the survival probability, depending on the traversed distance in the Earth. Earth effects provide the most model-independent signature of flavor oscillations. Ideally one would be able to compare the signals of two detectors, one of them shadowed by the Earth and the other not [37–40]. (An online tool is available to determine the shadowing probability for the next galactic SN depending on geographic location [41].)

Within the SN mantle and envelope, several modifications can occur, mostly relevant for the cooling phase when the shock wave has taken off. When it crosses the density region corresponding to the H-resonance, the MSW adiabaticity relevant for the "large Θ_{13} case" gets temporarily broken, imprinting a signature on the time-dependent $\bar{\nu}_e$ flux detectable at Earth. Moreover, there can be one or more reversed shocks and for some time several H-resonances arise because the density profile is not monotonic. Such features could serve as a diagnostic both for neutrino oscillation parameters and the astrophysics of shock-wave propagation [42–46]. On the other hand, the SN matter profile need not be smooth. Behind the shock wave, convection and turbulence can cause significant stochastic density variations that tend to wash out neutrino oscillation signatures [47–49].

3.3. Collective neutrino oscillations

The trapped neutrinos in a SN core as well as the neutrinos streaming off its surface are so dense that they provide a large matter effect for each other. The nonlinear nature of this neutrino–neutrino effect renders its consequences very different from the ordinary matter effect in that it results in collective oscillation phenomena. It was recognized only recently that these effects are important in SNe in the region up to a few 100 km above the neutrino sphere, even though typically the ordinary matter effect is much larger [50,51]. This insight has triggered a torrent of recent activities and has recently been reviewed [52].

Collective effects are important in regions where the effective neutrino–neutrino interaction energy μ exceeds a typical vacuum oscillation frequency $\Delta m^2/2E$. In an isotropic ensemble $\mu \sim \sqrt{2}G_F n_\nu$ with n_ν the neutrino density. The current–current nature of low-energy weak interactions implies that a factor $1 - \cos\theta$ appears in the interaction potential where θ is the angle between neutrino trajectories. If the background is isotropic this term averages to 1, but neutrinos streaming from a SN core become more and more collinear with distance, so the average interaction potential is reduced by a suitable average $\langle 1 - \cos\theta \rangle$. One finds that μ effectively decreases with distance as r^{-4} where two powers derive from the geometric flux dilution, another two powers from the increasing collinearity. Therefore, collective effects are important only fairly close to the neutrino sphere.

While one of the main points of collective effects is that they do not seem to be affected by dense background matter, this initial idea is not entirely correct. Actually when $n_e \gtrsim n_\nu$, matter effects do suppress collective phenomena after all [53], a condition that can be satisfied in an iron core SN during the accretion phase if the matter density is very large.

Let us assume that collective effects are not suppressed by matter, i.e., that the matter density is not too large in the "collective oscillation region". However, let us also assume that it is large enough and decreases slowly enough that the MSW resonances occur at larger distances. In this case collective effects and MSW conversions factorize. Let us further assume that we have a pronounced hierarchy of number fluxes $F_{\nu_x} \ll F_{\bar{\nu}_e} < F_{\nu_e}$ that certainly applies after bounce and during the accretion phase, but may not be valid during the cooling phase. In this scenario the impact of collective oscillations is straightforward. Nothing new happens for NH, whereas for IH the $\bar{\nu}_e$ flux is swapped with the $\bar{\nu}_x$ flux. In addition, the ν_e flux is swapped with the ν_x flux, but only for $E > E_{\rm split}$ where the energy $E_{\rm split}$ marks a sharp "spectral split", separating the swapped part of the spectrum from the unswapped part. $E_{\rm split}$ is fixed by the condition that the net ν_e flux $F_{\nu_e} - F_{\bar{\nu}_e}$ is conserved [54]. In other words, there is no net flavor conversion effect: essentially one has self-induced collective pair conversions $\nu_e\bar{\nu}_e \to \nu_x\bar{\nu}_x$.

An example is Fig. 1 where in the upper panels the flux spectra for ν_e, $\bar{\nu}_e$ and ν_x are shown as they leave the SN core. It is assumed that $L_{\nu_x} < L_{\bar{\nu}_e} = L_{\nu_e}$ with average energies $\langle E_{\nu_e} \rangle = 10$, $\langle E_{\bar{\nu}_e} \rangle = 14$ and $\langle E_{\nu_x} \rangle = 18$ MeV. In the lower panels the flux spectra after collective oscillations (but before MSW oscillations at larger distances) are shown. The spectral split in the neutrino spectra is conspicuous. Upon closer look a low-energy split in the anti-neutrino spectra is also visible (to be discussed below).

One expects no significant new effect during the deleptonization burst that is dominated by an almost pure ν_e flux. During the accretion phase, on the other hand, the overall scenario changes. Collective "pair conversions" represent an instability in flavor space and the dynamics is formally equivalent to that of an inverted pendulum [55]. This implies that the conversion occurs even for a very small value of Θ_{13} that has only a logarithmic impact on the radius where the conversion begins. Putting all of this together, one can construct Table 1 of survival probabilities [36]. Concentrating on the $\bar{\nu}_e$ detection channel, we note that in cases A–C one expects Earth effects. If Θ_{13} were measured to be large and the mass hierarchy to be inverted, observing Earth effects would imply that collective effects indeed take place in the SN environment because without them no Earth effects are expected in this case. On the other hand, if Θ_{13} were known to be small, laboratory experiments could not determine the mass hierarchy, whereas here the presence or absence of Earth effects distinguishes between the hierarchies even if Θ_{13} is extremely small [56].

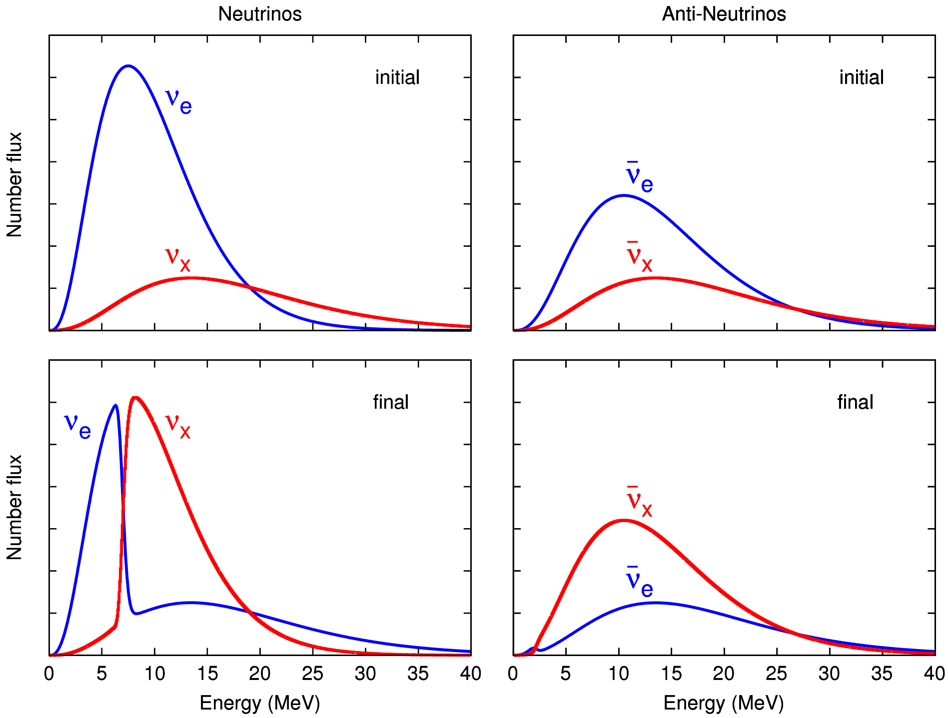

Fig. 1. Supernova neutrino spectra before and after collective oscillations for the example described in the text. They will be further modified by MSW effects at larger distances from the core.

Table 1
Survival probabilities including collective effects for the scenario described in the text.

Scenario	Hierarchy	$\sin^2 \Theta_{13}$	$p(E < E_{split})$	$p(E > E_{split})$	$\bar{p}(E)$	Earth effects
A	Normal	$\gtrsim 10^{-3}$	0	0	$\cos^2 \Theta_\odot$	$\bar{\nu}_e$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2 \Theta_\odot$	0	$\cos^2 \Theta_\odot$	$\bar{\nu}_e$
C	Normal	$\lesssim 10^{-5}$	$\sin^2 \Theta_\odot$	$\sin^2 \Theta_\odot$	$\cos^2 \Theta_\odot$	ν_e and $\bar{\nu}_e$
D	Inverted	$\lesssim 10^{-5}$	$\sin^2 \Theta_\odot$	0	0	–

The impact of collective effects described here (one spectral split in the ν_e spectrum and a complete swap of the $\bar{\nu}_e$ one) turns out to be a special case. In general, there are multiple spectral swaps and concomitant splits [57–60]. Analytic solutions to the nonlinear equations of motion are beginning to emerge, so these findings are no longer entirely numerical [59]. Explaining the theory of "stepwise spectral swapping" here would exceed the scope of this short review. (Animations showing how spectral swaps and splits develop as a function of radius from the SN are available at http://www.mppmu.mpg.de/supernova/multisplits.)

In principle, then, spectral splits can also occur in the $\bar{\nu}_e$ channel relevant for the existing large-scale detectors. However, if there is a realistic chance of observing them is less obvious because the required flavor spectra probably occur only during the cooling phase where spectral differences are anyway small and where shock-wave propagation and density fluctuation effects complicate the picture.

The entire situation becomes more complicated still if the matter density above the neutrino sphere declines so quickly with radius that collective effects and MSW resonances do not factorize or MSW effects even occur first and collective effects afterwards. This may be the case in the low-progenitor mass SNe of the O–Mg–Ne core class. In this case one may obtain an "MSW prepared spectral split" in the prompt ν_e burst [61–63].

Many questions about collective oscillations remain poorly understood at the moment, notably the issue of multi-angle decoherence, or rather, why some of the generic spectral swap features do not seem to depend on the fact that different angular neutrino modes interact differently with the overall neutrino background [64,65]. Another interesting question is three-flavor effects caused by radiative differences between ν_μ and ν_τ refraction [66–68] or possible CP effects caused by the Dirac phase in the neutrino mixing matrix [69].

4. Summary

More than twenty years after SN 1987A we are well prepared for the observation of another neutrino burst from a collapsing star, with Super-Kamiokande and IceCube the flagship experiments. In future, Super-Kamiokande may be upgraded with neutron-tagging capability, even bigger Cherenkov detectors may be built, and large-scale scintillator or liquid-Argon detectors may become available. The scientific harvest would be immense. Neutrinos will be excellent astrophysical messengers and allow us to follow stellar collapse and many of its details in situ, probably including short-time variations caused by convection and the SASI mode. From the particle-physics perspective, many of the unique lessons from SN 1987A could be refined. The question of neutrino flavor oscillations has received an intriguing twist by recognizing the importance of collective flavor oscillations. The interpretation of a neutrino signal in terms of neutrino mixing parameters will depend on many factors and requires a more complete theoretical understanding of these new effects. In preparation for the next galactic SN, both theorists and experimentalists have more work to do than just wait!

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