New opportunities with supernova neutrinos

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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.

1. INTRODUCTION

The neutrino observation of SN 1987A with about two dozen events remains the only detected astrophysical neutrino source other than the Sun. 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. A future megaton-class detector reaches as far as Andromeda at a distance of 780 kpc and large-scale scintillator or liquid-argon detectors can play an important role [1,2].

Galactic SNe are rare, perhaps a few per century [3] and the neutrino signal from the next nearby SN is a once-in-a-lifetime opportunity. Almost 30 years of nearly continuous neutrino sky coverage since 30 June 1980 when the Baksan Scintillator Telescope took up operation prove 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 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 [4].

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 concerning possible astrophysical lessons and neutrino flavor oscillations.

2. ASTROPHYSICAL LESSONS

Bethe and Wilson’s delayed explosion scenario [5] is the standard paradigm for core-collapse SNe. Spherically symmetric simulations have recently provided robust explosions for small progenitor masses of 8–10 $M_\odot$, the class of electron-capture SNe (or O-Mg-Ne-core SNe) [6]. For more massive stars, leading to the conventional iron-core SNe, strong deviations from spherical symmetry caused by large-scale convection and the standing accretion shock instability (SASI) are probably important [7–11], but full-fledged 3D simulations with sufficiently sophisticated neutrino transport are only beginning to come into reach. On average, the shock-wave radius is pushed to larger radii and allows the infalling material to absorb more energy, thus helping with the explosion [9].

A detailed neutrino light curve would go a long way towards testing the core-collapse paradigm. The SASI activity during the accretion phase would imprint itself upon the neutrino signal (Fig. 1). Assuming the 2D simulations of Ref. [10] provide a reasonable estimate of what is to be expected in a realistic case, can we observe this phenomenon with existing detectors?

Somewhat surprisingly, the best-suited instrument is IceCube which measures SN neutrinos by the increased noise level in the optical modules (OMs) [12–14]. The Cherenkov photons from the neutrino signal of a SN at roughly 10 kpc cause a signal comparable to the dark current in each OM, providing a hugely significant SN neutrino light curve when considering the noise correlation
of 4800 OMs. Each neutrino is detected with at most one Cherenkov photon, so every detected photon marks the arrival time of a different neutrino (unless it is background), whereas in Super-Kamiokande, every neutrino is detected by many photons, providing redundant arrival time information. Therefore, IceCube is almost optimal for reducing shot noise in that the Cherenkov photons are statistically uncorrelated.

In Fig. 1 (bottom) we show the expected counting rate in IceCube for the 2D model of Ref. [10], assuming one looks essentially in the direction of the dipolar SASI oscillation [15]. From an equa-

torial perspective, the signal variations would be smaller, but in a real SN it is unlikely that the oscillation direction would remain fixed in space. We also show the level of shot noise, assuming the signal is binned in 1 ms intervals. (IceCube actually uses a somewhat larger binning interval.) A megaton water Cherenkov detector would collect comparable statistics, whereas in Super-Kamiokande it would be difficult to detect fast time variations on this level, unless the SN is much closer than the fiducial 10 kpc.

It deserves mention that cosmological neutrino mass limits of about $m_\nu \lesssim 0.2$ eV are now so tight that ms variations would not be washed out by time-of-flight effects. Of course, this also implies that a SN neutrino burst is no longer useful for neutrino mass determination.

At a pessimistic SN distance of 20 kpc, both Super-K and IceCube can still time the onset of the neutrino signal and thus the bounce to within a few ten ms, comparable to the expected duration of the gravitational wave burst, allowing for an interesting correlation analysis [16,17].

All forms of radiation should suffer the same Shapiro time delay in the gravitational potential of the galaxy. For SN 1987A, 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 [18,19]. A millisecond-scale coincidence between neutrinos and gravitational waves would extend and refine this test.

An abrupt termination from black-hole formation would be another novel feature [20]. Likewise, recent simulations that include a description of quark matter predict a sharp $\bar{\nu}_e$ burst several hundred ms after the prompt $\nu_e$ burst [21].

The SN 1987A neutrino observations provided a unique confirmation of the overall picture of the core-collapse phenomenon. In detail, however, the observed $\bar{\nu}_e$ energies do not agree well with each other or with expectations, although more recent simulations with improved neutrino transport provide average energies much more in line with the SN 1987A measurements [22,23]. Either way, the sparse statistics simply do not allow for a detailed test of the spectral energies which thus has to await better data.
3. PARTICLE-PHYSICS LESSONS

The signal duration of the SN 1987A burst agrees well with expectations: 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 [24–31]. Far-reaching conclusions 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.

Spin-flavor conversions caused by the combined action of magnetic fields and matter effects can transform some of the prompt $\nu_e$ burst to $\bar{\nu}_e$, leading to a huge inverse-beta signal [32]. Such an observation would provide smoking-gun evidence for neutrino transition magnetic moments. Non-radiative decays would also produce a $\nu_e \rightarrow \bar{\nu}_e$ conversion during the prompt burst [33].

4. FLAVOR OSCILLATIONS

Neutrino oscillations require flavor-dependent fluxes. The species $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, and $\bar{\nu}_\tau$, collectively denoted as $\nu_x$, have only neutral-current interactions. Their flux spectra and detection cross sections are almost the same. On the other hand, $\nu_e$ and $\bar{\nu}_e$ have charged-current interactions, notably with protons, neutrons and nuclei, so we finally need to distinguish between the three species $\nu_e$, $\bar{\nu}_e$ and $\nu_x$. Oscillation effects can be summarized in terms of the energy-dependent $\nu_e$ survival probability $p(E)$ that gives us the $\nu_e$ flux at the detector as

$$F_{\nu_e}(E) = p(E)F_{\nu_e}^0(E) + [1 - p(E)]F_{\bar{\nu}_e}^0(E),$$

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 $\nu_e$ burst [35]. However, oscillation effects are hard to measure because existing and near-future detectors primarily see inverse beta decay $\bar{\nu}_e + p \rightarrow n + e^+$. In Super-Kamiokande, the prompt $\nu_e$ burst from a SN at 10 kpc would generate of order 10 events from $\nu_e$ scattering. In a megaton water-Cherenkov detector with neutron tagging [34], the $\nu_e$ burst would be a useful tool both for studying flavor oscillations and determining the SN distance [35]. Likewise, a large liquid-argon TPC would be a powerful $\nu_e$ detector [36].

During the subsequent accretion phase (that is short for low-mass progenitors) one finds $L_{\nu_e} \approx L_{\nu_x}$ and $\langle E_{\nu_e} \rangle > \langle E_{\nu_x} \rangle$. When the accretion phase is pronounced (for more massive progenitors), $L_{\nu_x}$ is much smaller than $L_{\nu_e} \approx L_{\nu_x}$, and the hierarchy of energies is significant [22,37]. 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 $\nu_x$ become quite similar and it will be much harder to see flavor oscillation effects in the dominant $\bar{\nu}_e$ detection channel.

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 $\Theta_{13}$. 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 $\sin^22\Theta_{13} \gtrsim 10^{-3}$ and non-adiabatic for $\sin^22\Theta_{13} \lesssim 10^{-5}$. Therefore, the neutrino burst is, in principle, sensitive to $\Theta_{13}$ and the mass hierarchy [38,39].

The $\nu_e$ and $\bar{\nu}_e$ survival probabilities in the SN mantle and envelope get modified by regeneration effects in the Earth if the SN is observed “shadowed” by the Earth. Earth matter effects result in a characteristic energy-dependent modu-
lation of the survival probability and 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 [40–44].

The neutrinos streaming from a SN core are so dense that they provide a large matter effect for each other. The nonlinear nature of this neutrino-neutrino effect 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 [45–47]. This insight has triggered a torrent of recent activities [48].

Let us assume that the matter profile is such that the MSW resonances occur at larger distances than collective oscillations, a condition that should be satisfied during the accretion phase. Let us further assume that we have a pronounced hierarchy of number fluxes $F_{\nu_e} < F_{\bar{\nu}_e}$ and $F_{\nu_x}$. 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 $\nu_x$ flux. In addition, the $\nu_e$ flux is swapped with the $\nu_x$ flux, but only for $E > E_{\text{split}}$ where the energy $E_{\text{split}}$ marks a sharp “spectral split,” separating the swapped part of the spectrum from the unswapped part. $E_{\text{split}}$ is fixed by the condition that the net $\nu_e$ flux $F_{\nu_e} - F_{\bar{\nu}_e}$ is conserved [49]. In other words, there is no net flavor conversion effect: essentially one has self-induced collective pair conversions $\nu_e \bar{\nu}_e \rightarrow \nu_x \bar{\nu}_x$.

An example is Fig. 2 where the upper panels show the flux spectra for $\nu_e$, $\bar{\nu}_e$ and $\nu_x$ as they leave the SN core. It is assumed that $L_{\nu_e} < L_{\bar{\nu}_e} = L_{\nu_x}$ with average energies $\langle E_{\nu_e} \rangle = 10$, $\langle E_{\bar{\nu}_e} \rangle = 14$ and $\langle E_{\nu_x} \rangle = 18$ MeV. The lower panels show the flux spectra after collective oscillations, but before MSW oscillations. The spectral split in the neutrino spectra is conspicuous.

Therefore, the neutrino oscillation scenario changes entirely during the accretion phase. Collective “pair conversions” represent an instability in flavor space; the dynamics is formally equivalent to that of an inverted pendulum [50]. This implies that the conversion occurs even for a very small value of $\Theta_{13}$. Putting all of this together, one can construct Table 1 of survival probabilities [39]. Concentrating on the $\bar{\nu}_e$ channel, we note that in cases A–C one expects Earth effects. If $\Theta_{13}$ 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 $\Theta_{13}$ 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 $\Theta_{13}$ is extremely small [51,52].

The impact of collective effects described here (one spectral split in the $\nu_e$ spectrum and a complete swap of the $\bar{\nu}_e$ one) is a special case. In general, there are multiple spectral swaps and concomitant splits [53–56]. In principle, 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.

![Figure 2](image-url) Supernova neutrino spectra before and after collective oscillation. They will be further modified by MSW effects at larger distances.
Table 1
Survival probabilities including collective effects for the scenario described in the text.

<table>
<thead>
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<th>Scenario</th>
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<th>$\sin^2 \Theta_{13}$</th>
<th>$p(E&lt;E_{\text{split}})$</th>
<th>$p(E&gt;E_{\text{split}})$</th>
<th>$\bar{\nu}_e$</th>
<th>Earth effects</th>
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<td>0</td>
<td>$\cos^2 \Theta_{13}$</td>
<td>$\nu_e$</td>
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<tr>
<td>B</td>
<td>Inverted</td>
<td>$\lesssim 10^{-3}$</td>
<td>$\sin^2 \Theta_{13}$</td>
<td>0</td>
<td>$\cos^2 \Theta_{13}$</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>C</td>
<td>Normal</td>
<td>$\lesssim 10^{-5}$</td>
<td>$\sin^2 \Theta_{13}$</td>
<td>$\sin^2 \Theta_{13}$</td>
<td>$\cos^2 \Theta_{13}$</td>
<td>$\nu_e$ and $\bar{\nu}_e$</td>
</tr>
<tr>
<td>D</td>
<td>Inverted</td>
<td>$\lesssim 10^{-5}$</td>
<td>$\sin^2 \Theta_{13}$</td>
<td>0</td>
<td>0</td>
<td>—</td>
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</table>

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 [57–60].

5. 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 effects. 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!

ACKNOWLEDGMENTS

This work was partly supported by the Deutsche Forschungsgemeinschaft, Grant No. TR-27 “Neutrinos and Beyond” and the Cluster of Excellence “Origin and Structure of the Universe.”

REFERENCES
