Neutrino Burst from SN1987A and the Solar-Neutrino Puzzle

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The prompt ν_e signal from the supernova explosion in the Large Magellanic Cloud presumably detected by Kamiokande II does not necessarily mean that the Mikheyev-Smirnov-Wolfenstein effect on the solar-neutrino flux is not operative. The electron neutrino, once rotated to a different-flavor neutrino in the progenitor star, can come back via the matter oscillation effect in the Earth, or a residual ν_e flux from the progenitor can directly hit the detector, saving the Mikheyev-Smirnov-Wolfenstein explanation of the solar-neutrino problem for a range of mixing parameters.

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The neutrino burst from SN1987A in the Large Magellanic Cloud, first discovered by Hirata *et al.*[1] (the Kamiokande II collaboration) and later confirmed by Bionta *et al.*[2] [the IMB (Irvine-Michigan-Brookhaven) group], gives a unique opportunity to explore the physics of supernova explosions. It is remarkable that gross features of these neutrino events, event rate, average neutrino energy, and time span, agree with theoretical calculations based on conventional models of the stellar collapse.[3] It is the first time in the history of modern science that dynamics of the stellar collapse, on the time scale of less than 10 sec, has been probed, with a positive result.

A closer examination of these events, however, reveals some unusual features that seem difficult to reconcile with the standard calculation. These may have interesting astrophysical and particle-physics implications.[4-6] In this paper we shall pay particular attention to the first forward events of Kamiokande II suggestive of the prompt neutronization burst and examine what they mean in the context of basic properties of the neutrino and how they are related to the solar-neutrino problem.

Recall that the basic process of detection in the water Cherenkov facility is $\nu_e+e\rightarrow\nu_e+e$ for the electron-type neutrinos and $\bar{\nu}_e+p\rightarrow e^++n$ for electron-type antineutrinos. The similar processes induced by ν_H and $\bar{\nu}_H$ ($H=\mu$ or τ) are unlikely to occur, since they have smaller cross sections. The former reaction (ν_e+e) is characterized by the directionality of the recoil electron in a forward cone of about 15°, while the latter ($\bar{\nu}_e+p$) yields an isotropic distribution of e^+ for neutrino energy of $\simeq 10$ MeV. It is thus natural to associate the first one or two forward (within $18°\pm18°$ and $15°\pm27°$ cone) events of the Kamiokande II observation with the prompt ν_e burst. The probability of finding two forward events within 42° out of randomly distributed $\bar{\nu}_e$ events is small, $\simeq 0.6\%$. The standard calculation[3] also supports this interpretation: Other types of neutrinos are not much emitted at the first instant. A potentially serious problem[5] that may be raised with this interpretation is that in the calculation of Wilson and co-workers, the yield of prompt ν_e events is much less ($\simeq 0.3$ event in Kamiokande II) and the observed duration of $\simeq 100$ ms between the first two events is too large. These two features are, however, nicely explained in the advective overturn model of Arnett.[7] This uncertainty in astrophysical models casts a doubt on interpreting the second event as the ν_e signal. The ambiguity is hoped to be resolved by future observations, but for the following analysis we shall assume that the first one or two events were caused by $\nu_e e$ scattering, mentioning parameter ranges in two cases. As pointed out in Ref. 4 and also by Walker and Schramm[8] prior to the supernova event, the prompt ν_e signal appears then to rule out the Mikheyev-Smirnov-Wolfenstein mechanism[9] of neutrino oscillation as a possible explanation of the solar-neutrino deficit,[10] because the ν_e burst generated at the core is converted to another type of neutrino (ν_μ or ν_τ) in passing through the outer region of the progenitor star, which is not dissimilar to the sun in its density.

This conclusion rests on the assumption that the conversion is very efficient in the progenitor star and that nothing drastic happens until the converted neutrino arrives at the detector. We have examined carefully whether this is true and, surprisingly, found that there are two possibilities to save the Mikheyev-Smirnov-Wolfenstein explanation: a possibility of the prompt ν_H being converted back to ν_e within the Earth, and the possibility of a sizable ν_e residual in the progenitor. These two cases can occur in different parameter regions of δm^2 and $\sin 2\theta$ that can then be tested in forthcoming experiments. These parameter regions differ somewhat, depending on whether one accepts the second event as due to $\nu_e e$ scattering.

The effects of neutrino oscillation in the Earth have been discussed in the literature.[11] As an idealization, consider the Earth to have a constant density of ρ_0 and an electron fraction of Y_e ($\simeq 0.5$ in the mantle). The neutrino in a mass eigenstate ν_2, defined by $(\sin\theta)\nu_e + (\cos\theta)\nu_H$, of energy E incident on Earth may undergo an oscillation into ν_e with a probability given by (n_e = electron density)

$$P(l) = \sin^2\theta\{\cos^2\omega l + [(\delta m^2/4E\omega)(1+2\sqrt{2}G_F n_e E/\delta m^2)]^2 \sin^2\omega l\} \quad (1)$$

after passing a distance l in Earth. Mixing parameters in vacuum are denoted by the mass-squared difference $\delta m^2 = m_2^2 - m_1^2$, and the angle θ. The frequency ω is given by

$$\omega = (\delta m^2/4E)\cos 2\theta[(\rho/\rho_0 - 1)^2 + \tan^2 2\theta]^{1/2}, \quad (2)$$

$$\rho_0 \simeq (13 \text{ g cm}^{-3})\cos 2\theta (Y_e/0.5)^{-1}[\delta m^2/(10^{-5}\text{ eV}^2)][E/(10 \text{ MeV})]^{-1}. \quad (3)$$

At the resonance $\rho = \rho_0$ and $P = \sin^2\theta\cos^2\omega l + \cos^2\theta\sin^2\omega l$, where

$$\omega l = \frac{\delta m^2}{4E} l \sin 2\theta \sim \frac{\pi}{2}\frac{\sin 2\theta}{0.31}\frac{\delta m^2}{10^{-5}\text{ eV}^2}\frac{10\text{ MeV}}{E}\frac{l}{4000\text{ km}}. \quad (4)$$

Most intriguingly, the Kamiokande II detector at the time of the neutrino burst (23 February 1987, 7:35:35 UT) was located in a fortunate place such that the neutrino had a path length of $\simeq 4100$ km in the mantle region of the Earth, at densities of $\rho_0 = 3$–4 g cm^{-3}. Thus both the resonance condition with (3) and the condition for maximal conversion, $\omega l = \pi/2$, are met for the Kamiokande burst if

$$[\delta m^2/(10^{-5}\text{ eV}^2)][E/(10\text{ MeV})]^{-1}\cos 2\theta \simeq 0.3, \quad (5)$$

$$\tan 2\theta \simeq 1. \quad (6)$$

With an average energy of 25 MeV for the first two forward Kamioka events, the parameter values of δm^2 and θ given by (5) and (6) roughly lie in the region required by the solar-neutrino experiment of Davis and others.[10]

For a more detailed study we numerically integrated the evolution equation of two neutrino components, ν_e and ν_H, taking a more realistic, position-dependent density profile of the Earth.[12] As shown by Ref. 11, we found an oscillation pattern of varying amplitude according to variation of densities as the path length l increases, a feature that cannot be understood by the analytic formula (1). Assuming the average energy of 25 MeV, we searched for a region in the parameter space that can account for the forward ν_e events in Kamiokande II. In Fig. 1 is plotted the region of parameters $(\delta m^2, \sin^2 2\theta/\cos 2\theta)$ that gives rise to a more than 50% conversion of $\nu_2 \to \nu_e$ in Earth. These regions well overlap the space that can explain, as a result of the matter oscillation effect in the sun, the Cl experiment at the 1σ level. This parameter range of neutrino mixing, $\delta m^2 = (0.2$–$1)\times 10^{-5}$ eV^2, $\sin^2\theta = 0.2$–0.3, is compatible with all laboratory and underground experiments.[14] If one takes a neutrino energy 32 eV appropriate for the first event, the δm^2 range is shifted upward by a factor of $\frac{32}{25}$.

We also checked whether the adiabatic conversion of the electron-type neutrino is very effective at the site of production. Generally speaking, the parameter region $(\delta m^2, \sin^2 2\theta/\cos 2\theta)$ relevant to the matter oscillation is enlarged for the giant star, mostly because of a larger density and a smaller density gradient, $-d(\ln\rho)/dr$, in the outer region of the progenitor star. The power-law behavior of the density in the relevant progenitor region as indicated by a very recent presupernova calculation[15] is to be contrasted with an approximate exponential decrease in the sun, which necessitates a more careful examination of the relevant parameter region.

The ν_e fraction P_e, when the burst leaves the star, can be estimated by the use of the analytic formula of Ref. 13:

$$P_e \simeq \sin^2\theta + (\cos 2\theta)\exp[-0.7(\delta m^2_{-4})^{1/2}(\sin^2 2\theta/\cos 2\theta)_{-3}(\cos 2\theta)^{-1/2}(E_{25})^{-1/2}]. \quad (7)$$

In deriving this equation, a density profile of $\rho \simeq 50$ g cm^{-3} $(r/0.1R_\odot)^{-2}$, in the He shell of a 13-$M_\odot$ star[15] was taken, which holds in the relevant resonance region. Convenient units were used in (7): $\delta m^2_{-4} = \delta m^2/(10^{-4}$ eV$^2)$, $(\sin^2 2\theta/\cos 2\theta)_{-3} = 10^3(\sin^2 2\theta/\cos 2\theta)$, $E_{25} = E/(25$ MeV). A region of the parameter space $(\delta m^2, \sin^2 2\theta/\cos 2\theta)$ is determined such as to yield more than 50% ν_e before the burst enters the Earth. This region cuts off 1.8–2.4-SNU (solar neutrino units) contours of the Cl experiment at the upper left corner, as shown in Fig. 1. For solar model B of Ref. 13 a small region with $\delta m^2 \simeq 0.8\times 10^{-4}$ eV^2 and $\sin 2\theta \simeq 0.03$ is thus not excluded and can equally well explain both the solar-neutrino experiment and the prompt ν_e signal of Kamiokande II. For the estimated neutrino energy of the first event alone, the allowed region is slightly enlarged by the upward shift of $\frac{32}{25}$. This parameter range falls in a region of great interest in some grand-unification-theory models.[16]

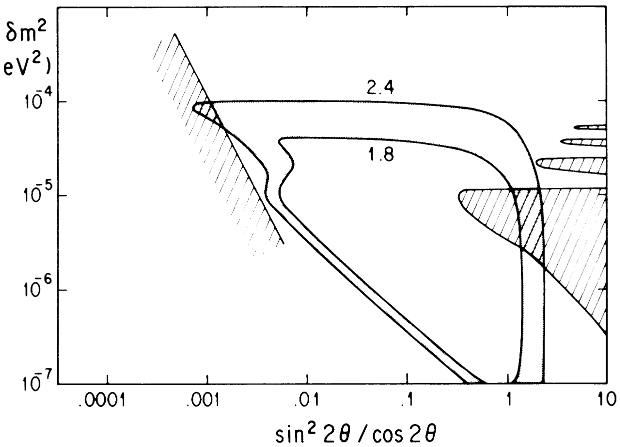

FIG. 1. Parameter regions of δm^2 and $\sin^2 2\theta/\cos 2\theta$ that can account for the reduced neutrino flux of Cl experiment (2.1 ± 0.3 SNU), and more than 50% conversion of $\nu_2 \rightarrow \nu_e$ in Earth (right shaded patches) or 50% residual ν_e flux from the 13-$M_\odot$ progenitor (left shaded region) for the Kamiokande burst. Iso-SNU contours of 1.8 and 2.4 SNU were adopted from Solar Model B of Ref. 13.

We should caution that this small-angle solution is sensitive to the details of the density profile. A more general power-law density profile of $\rho \propto r^{-\alpha}$ yields a nonadiabatic oblique line, roughly $(\delta m^2)^{1-1/\alpha}\sin^2 2\theta = \text{const}$, which is not parallel to the sun's nonadiabatic line and hence capable of crossing this line. The ultimate selection of the correct presupernova model should be made after more observational data are accumulated and comparison with theoretical calculations are achieved.

The preceding discussions assume that only two types of neutrino are relevant to matter oscillation effect, both in the star of neutrino production and in the Earth. The chance that these two neutrino flavors are different in the cases of the solar problem and the SN1987A burst, for instance, $\nu_e \leftrightarrow \nu_\mu$ for the sun and $\nu_e \leftrightarrow \nu_\tau$ for the supernova, appears slim if one considers a hierarchical mass pattern[16] for three massive neutrinos. The fact that an electron neutrino from the supernova was observed means that either the ν_e never oscillates, or once rotated ν_e comes back in Earth. The latter possibility requires that the mass and mixing of the relevant neutrino (ν_μ or ν_τ) should lie in the range which is also relevant to the solar-neutrino problem; hence the two heavier neutrinos relevant to the supernova burst and the solar-neutrino problem are the same, unless "ν_μ" and "ν_τ" (second and third mass eigenstates) are almost degenerate. Therefore our analysis given above does not need modification except for a particular, contrived case.

The implications of our finding are most immediate to the solar-neutrino puzzle. It predicts the forthcoming Ga experiment[17] to yield[13] 40–60 SNU, or $\simeq 120$ SNU (whose precise range sensitively depends on the progenitor model and fraction of the conversion), depending on two different mechanisms.

In summary, we demonstrated that even if the first forward events of Kamiokande II are caused by the prompt ν_e signal, the Mikheyev-Smirnov-Wolfenstein matter oscillation effect may operate in the sun. In one case the neutrino may have been rotated twice back to the original ν_e, first oscillating in the progenitor star and then oscillating back in Earth. In the other case an incomplete rotation in the progenitor can give a sufficient ν_e component in the detector, although in this case the precise parameter range of δm^2 and $\sin^2 2\theta$ compatible with the reduced Cl rate is sensitive to details of the progenitor model. Our suggested solution should be taken with care, because our considerations are based on small-statistics data.

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