MASSIVE DIRAC NEUTRINOS AND THE SN1987A SIGNAL

RAJ GANDHI*
Physics Department, University of Arizona, Tucson, AZ 85721

ABSTRACT

I discuss results of calculations which incorporate the effect of massive Dirac neutrinos in numerical models for the cooling of the neutron star associated with SN1987A. In the Weinberg-Salam standard model, minimally extended to include Dirac neutrino masses, the production of sterile (positive helicity) neutrinos via neutral-current neutrino-nucleon scattering proceeds at a rate that significantly affects the energetics of cooling. We determine the expected number of events, total energy in neutrinos and the burst duration for both Kamiokande II and Irvine-Michigan-Brookhaven detectors. Due to an increase in the cooling rate caused by sterile neutrinos, we find that for $m_{\nu_{\mu,\tau}} = \sqrt{m^2_{\nu_\mu} + m^2_{\nu_\tau}} \geq 14$ keV, the expected neutrino burst is shortened to a duration that is inconsistent with the observations reported by both detectors. The calculations incorporate the feedback effects of the cooling due to sterile neutrinos in a self-consistent manner and the mass limit obtained is found to be largely insensitive to the equation of state used.

I. Introduction

The observation of the neutrino signal [1] from the Type II supernova, SN1987A, by the Kamiokande II (KII) and Irvine-Michigan-Brookhaven (IMB) detectors has provided important confirmation of some major features of supernova theory. In addition, it has yielded important new constraints for particle physics in the form of limits on the masses, charges, lifetimes, couplings, and magnetic moments of neutrinos and weakly interacting particles proposed in various extensions to the Standard Model [3-9].

The detection of 11 neutrino events over a period of ~ 12 seconds by KII and 8 neutrino events over ~ 6 seconds by IMB, yield, as their most significant conclusion, that thermal neutrinos with an approximate temperature of 4-5 MeV did, as theoretically predicted, carry away the bulk ($\geq 99\%$) of the $2 - 4 \times 10^{53}$ ergs of the gravitational binding energy released. As discussed, for instance, in references [10], theoretical protoneutron-star predictions that the burst would last several seconds were borne out by the observations. As shown in Refs. [10,11,12], the data also contain information which excludes the possibility that this duration is a consequence of the dispersive effects of a massive electron-neutrino.

This several-second duration is a sensitive indicator of the rate at which cooling occurred. In other words, it serves to provide constraints on any particle which can appreciably accelerate the cooling process to a degree that conflicts with observation. If the Weinberg-Salam [13,14] standard model is minimally extended to include Dirac masses for the (relativistic) neutrinos pair-produced in the core of the star, then an avenue for rapid cooling is provided without including any non-standard interactions or couplings [6]. In this talk I present results incorporating the effect of these masses into numerical models for the cooling of a neutron star in a self-consistent manner, including feedback effects, and determine the expected response of the KII and IMB detectors. Specifically, we calculate the burst duration and the number of events for each detector and the neutrino energy released in the explosion. The calculations, in conjunction with the observed burst duration, yield a mass limit of ~ 14 keV for μ- and τ- neutrinos. Protoneutron star cooling models, however, have a major source of uncertainty: the equation of state (EOS) (which could be relatively stiff or soft). To determine the sensitivity to the EOS of the mass limit obtained, it was necessary to perform calculations with two different models [15,16]. Fortunately, we find that variations in the EOS do not affect the results to a significant degree.

II. Massive Dirac Neutrinos and Their Role in the Cooling of Neutron Stars

The Weinberg-Salam standard model assumes massless neutrinos, excluding both Dirac and Ma-

* This work was done in collaboration with Adam Burrows.

jorana mass terms. The former is absent in the Lagrangian due to the absence of any right-handed neutrino, ν_R, and the latter term is forbidden by a global symmetry which conserves lepton number and is a result of the minimal Higgs structure in the model. However, the question of whether neutrinos are massive is crucial to progress beyond the current level of understanding in particle theory, since at present we have no inkling of the origin of fermion masses. The current bounds from particle physics are $m_{\nu_e} \sim 15$ eV, $m_{\nu_\mu} \sim 250$ keV, *and* $m_{\nu_\tau} \sim 35$ MeV [17]. Given the relatively high values of the bounds on the $\mu-$ and $\tau-$ neutrino masses, it is useful to obtain as much information as possible on their values from astrophysics and cosmology.

If neutrinos have a Dirac mass, then their chirality eigenstates (ν_L, ν_R) are superpositions of helicity (λ) eigenstates (ν^-, ν^+), with $\lambda = \vec{\sigma}.\vec{p} = \pm 1$. A relativistic left-handed (right-handed) neutrino, ν_L (ν_R), is predominantly in the $\lambda = -1$ $(\lambda = +1)$ state, with admixtures of order $\frac{m}{E}$ of the opposite helicity. Thus, by the Z^o exchange process shown in Fig. 1, a massive relativistic neutrino can flip its helicity and emerge almost right-handed in a scattering process involving an electron or nucleon, as it diffuses out of the newborn neutron star. Such a neutrino would be non-interacting in the standard theory and escape on a much smaller timescale, accelerating the cooling process and altering the burst duration. These processes have been discussed in Ref. [6]. Here we use a general equation for the above scattering process derived in that paper (equation 20, Ref. 6) which gives the differential

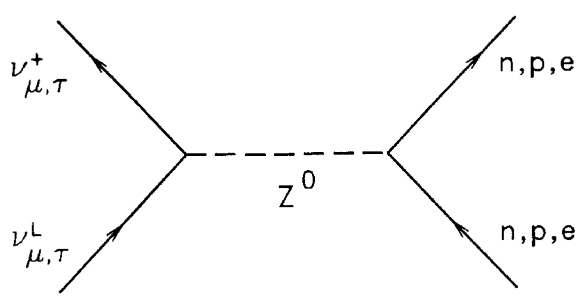

Fig. 1: The Z^o exchange process in which a left-handed neutrino (ν^L) emerges in the final state with positive helicity (ν^+). For relativistic energies such a neutrino leaves the core of the neutron star on time scales much shorter than the diffusion time of several seconds.

flip cross section for a μ- or τ- neutrino of mass m scattering off an electron or nucleon of mass M in the center-of-mass frame:

$$\left[\frac{d\sigma}{d\Omega}\right]^{flip}_{c.m.} = \frac{G_F^2}{16\pi^2 s} m^2 [p^2 (c_V - c_A)^2 (1 - \cos^2\theta) - M^2 (c_V^2 - c_A^2)\cos\theta + M^2 (c_V^2 + 3c_A^2)]. \quad (1)$$

Here p is the 3-momentum of either particle and θ is the angle made by the scattered neutrino with its initial direction, while s is the center-of-mass energy squared. G_F is the Fermi coupling and c_V, c_A are the weak interaction vertex factors appropriate to the target. For both electron and nucleon targets, this leads to total cross sections which are relatively insensitive to neutrino energy. For our calculations we use only the neutrino-nucleon cross section, which is significantly greater than the one for neutrino-electron scattering.* A value of $3 \times 10^{-47} \left(\frac{m}{50\text{keV}}\right)^2$ cm^2 has been used for the total cross section. It represents an approximate average over neutrino-proton and neutrino-neutron flip cross sections obtained over the relevant range of energies by integrating the expression in equation (1) above. We note that the total energy released in sterile neutrinos will be proportional to $m^2_{\nu_{\mu,\tau}} = m^2_{\nu_\mu} + m^2_{\nu_\tau}$.

III. Description of the Neutron Star Cooling Models and the Numerical Code

Our work uses the protoneutron star evolution codes of Burrows and Lattimer [16] and Burrows [15] modified to include the back reaction of cooling caused by massive neutrinos. It thus takes into account the effect of flipped neutrino-induced

* A full calculation would include both the $\nu - e$ scattering process and the pair-production of flipped neutrinos, which can be significant in the very early times after collapse. The second process has been discussed in Ref [18]. We also note that neutrino-nucleon and neutrino-electron scattering can lead to helicity flips via the neutrino magnetic moment. Although the cross sections for these are also proportional to m^2, in the Standard Model they are highly suppressed compared to the Z^o process considered here, being a higher-order correction.

temperature decreases on subsequent (temperature-dependent) neutrino emission. This enables us to address the effect of neutrino mass on the burst duration seen by KII and IMB in a quantitative and self-consistent manner. The code solves the general-relativistic equations of stellar structure using standard relaxation techniques. Assuming the neutrinos to be thermalized with the local matter temperature and to be emitted with a Fermi-Dirac energy distribution, it follows all six neutrino species (three neutrinos and their charge conjugates) and uses a sophisticated neutrino opacity algorithm.

Once the core of a massive star exceeds the Chandrasekhar limit ($\sim 1.4 M_\odot$) and implodes, collapse continues until supranuclear densities are reached. The matter then stiffens, causing the inner core to rebound into the outer core, giving birth to a shock wave. The inner star then rapidly achieves hydrostatic equilibrium, undergoing neutronization and cooling over a timescale of several seconds. This is also the time over which the surplus gravitational binding energy is released in the form of neutrinos and anti-neutrinos of all species. In contrast, shock wave formation has an associated timescale of milliseconds. The cooling and diffusion timescale (and, hence, the duration of the burst detected by KII and IMB) for the neutrinos is set by their weak-interaction mean-free-paths at supranuclear densities. The neutrino signal can be separated into two phases. The first of these, occurring over $\sim 1-2$ seconds, is emission marking the cooling of the outer mantle, powered by its quasistatic collapse and by residual accretion. The second phase, lasting several seconds, represents inner core cooling and is powered by neutrinos transporting energy from it. Since the gravitational energy released is known to be $\sim 2-4\times 10^{53}$ ergs, energy transport by flipped neutrinos, which would occur over light-travel time scales for the core, has to be at the expense of 'normal' neutrino emission, altering the detected signal.

Two protoneutron star models, A and B, were evolved for different neutrino masses for 10 seconds after bounce. The published detector fiducial masses, efficiencies, and energy thresholds were used, in conjunction with the flipped and unflipped neutrino cross sections and a supernova distance of 50 kpc to calculate the expected signals for both KII and IMB detectors. The first model, A, which is model 55 from Ref [15], has a stiff EOS and starts at a mass of $1.3 M_\odot$ and accretes to a mass of $1.5 M_\odot$. Its accretion rate is exponential and has a time constant of 0.5 secs. Model B is model 62 from Ref [15], which is identical in all ways to Model A, but has a soft EOS. The initial lepton and entropy profiles that the models use are typical of those found in the collapse literature [15]. These choices thus test the sensitivity of our results to the EOS, which, apart from the initial rotational structure, is perhaps the most uncertain ingredient in collapse calculations.

IV. Discussion of Results

Table I and Figs. 2, 3 and 4 summarize the results obtained from the protoneutron-star calculations for various values of $m_{\nu_{\mu,\tau}} = \sqrt{m_{\nu_\mu}^2 + m_{\nu_\tau}^2}$ (0-25 keV). Fig. [2] shows, for the first 10 seconds, the radiated total energy, E_T, and the total energy in sterile neutrinos, E_f. The feedback effect due to cooling is manifest in this figure. Although both models A and B have total energy losses of ~ 200 foes (1 foe = 10^{51} ergs) for massless neutrinos, as

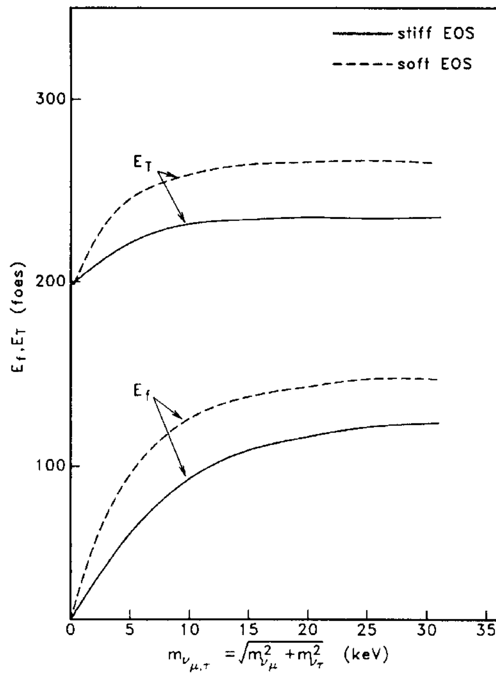

Fig. 2: The total energy released in all types of neutrinos, E_T and the energy lost via flipped neutrinos, E_f, as a function of $m_{\nu_{\mu,\tau}}$ for both stiff and soft equations-of-state.

Table I

$m_{\nu_{\mu,\tau}}$(keV)	Number of events expected		Emitted Energy ($\times 10^{51}$ ergs)		Δt (90%) (secs)		Δt (70%) (secs)	
	KII	IMB	E^f_ν	E^L_ν	KII	IMB	KII	IMB
			Model A (stiff, 1.3 → 1.5 $M_\odot$)					
0	10.15	5.275	*	197.65	6.0	3.65	2	0.9
5	8.91	4.785	55	225	4.3	2.1	1.3	0.54
10	7.8	4.38	92	239	2.8	1.25	0.83	0.35
15	7.11	4.1	109	243	1.7	0.9	0.65	0.27
20	6.69	3.92	119	244	1.35	0.75	0.55	0.23
25	6.38	3.77	124	244	1.17	0.65	0.48	0.19
30	6.13	3.64	130	245	1.0	0.57	0.43	0.18
			Model B (soft, 1.3 → 1.5 $M_\odot$)					
0	10.3	5.58	*	194	6.1	4.05	2.08	0.92
5	8.62	4.87	95	254	3.6	1.9	0.99	0.53
10	7.65	4.48	131	271	2.0	1.1	0.73	0.37
15	7.18	4.28	146	277	1.45	0.9	0.6	0.3
20	6.82	4.07	153	279	1.22	0.7	0.53	0.24
25	6.55	3.91	158	281	1.1	0.6	0.4	0.20

$m_{\nu_{\mu,\tau}}$ increases, the rise in E_T and E_f is relatively modest, in spite of the fact that $E_f \propto m^2_{\nu_{\mu,\tau}}$. For instance, model A shows that as $m_{\nu_{\mu,\tau}}$ increases from 2 keV to 20 keV, E_f goes from approximately 20 foes to 120 foes, an increase by a factor of 6 instead of a 100. For the same mass range, the corresponding rise for model B is roughly a factor of 4, from $\sim$ 40 foe to $\sim$ 150 foe. The reason for this is that the temperature dependence of E_f is steep [6], ($\propto T^4$), causing losses due to the mass effect to be self-quenching. This back-reaction is also reflected in Fig. [3], which shows the number of events which would have been detected by KII and IMB after 10 secs for various values of neutrino mass. Even for relatively large masses, the reduction in the number of detected events is moderate, especially for the IMB detector. The results are thus not inconsistent with observations, even if mass effects lead to significant energy losses in the form of positive helicity neutrinos.

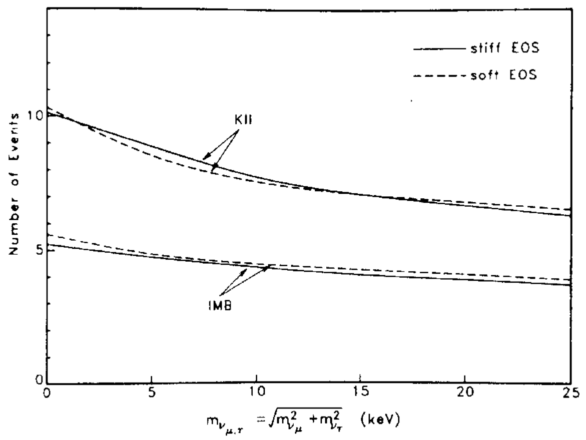

Fig. 3: The expected number of events for both the KII and IMB detectors as a function of $m_{\nu_{\mu,\tau}}$, for model A (stiff EOS) and model B (soft EOS).

However, in Fig. 4 we have a quantity that is indeed a sensitively varying function of the neutrino mass in the relevant range. The plot for Δt(90%) and values for Δt(70%) (Table I), the

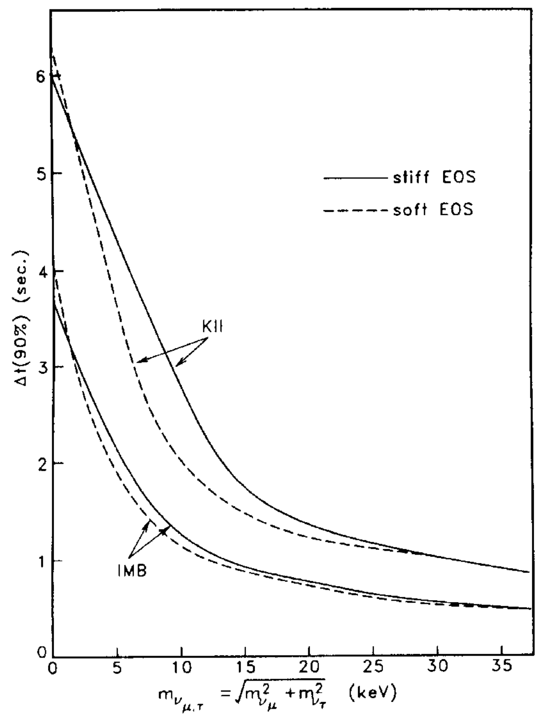

Fig. 4: The time taken for the accumulated number of events to reach 90% of the final total number of events as a function of $m_{\nu_{\mu,\tau}}$, for both detectors and both models.

times it takes for the accumulated number of events, to reach 90% and 70%, respectively, of the final total number of events, demonstrate this. For neutrino masses of $\sim$ 14 keV, $\Delta t(90\%)$ drops by a factor of 3 or more for both models and both detectors, clearly inconsistent with the observed long duration of the burst at both locations. The same is true of $\Delta t(70\%)$. As mentioned above, the neutrino emission occurs in two phases, the first $\sim$ 1 sec phase due to outer mantle heating and accretion and the second several-second phase powered by inner core energy. Hence, if the inner core emission dwindled due to flipped neutrinos draining energy on light-travel time scales, the observed neutrino flux would dive sharply after $\sim$ 1 sec, in conflict with what was seen by KII and IMB. These considerations thus suggest a conservative limit of $\sim$ 14 keV on the Dirac mass of $\mu-$ and $\tau-$ neutrinos. This limit thus refines and substantiates previous work [6,8] by including neutrino mass effects and their back-reaction on protoneutron-star cooling in a self-consistent manner. As Figs. 3 and 4 demonstrate, feedback effects are important in making comparisons with observations using stellar evolution calculations.

V. Conclusion

We have incorporated the effects of massive (relativistic) Dirac neutrinos into numerical models of the initial cooling of the newborn neutron star associated with SN1987A. The major effect on the cooling process is the rapid energy loss caused by the helicity flip process occurring via Z^o exchange, when $\mu-$ and $\tau-$ neutrinos scatter off nucleons in their outward diffusive passage through the core. In the Standard Model of Weinberg and Salam, minimally extended to include a Dirac mass term for neutrinos, positive helicity neutrinos are almost completely non-interacting and escape on very different time scales compared to their left-handed counterparts. This affects the characteristics of the neutrino burst emitted. Using the published detector response parameters for KII and IMB detectors in conjunction with predictions of the expected neutrino pulse characteristics, we address the question of which neutrino mass range gives results consistent with observations. We self-consistently determine the total number of events, total energy, energy in flipped neutrinos and the burst duration. The burst duration exhibits the most sensitivity to mass effects and is used to obtain a conservative limit on $\mu-$ and $\tau-$ neutrino masses of $\sim$ 14 keV. For this value, the pulse duration is shortened by a factor of 3 or more for both detectors, in obvious contradiction with observations. In contrast, the energy carried away by flipped neutrinos is roughly half the total energy emitted, and the number of events is $\sim$ 8 for KII and $\sim$ 5 for IMB, not inconsistent with observations.

Perhaps the most important uncertainty involved in determining our limit is the EOS at supranuclear densities. We have made an effort to minimize this by performing calculations using both a stiff and a soft EOS and find that the burst duration is not a highly sensitive function of this, giving us a reliable limit on neutrino mass. Finally, we need to address the question whether, for $\tau-$ neutrinos, the arguments presented here do rule out all masses between $\sim$ 14 keV and the current bound from accelerators, $\sim$ 35 MeV. Neutrino energies in the core are of the order of 50-100 MeV. In the unlikely event that the τ- neutrino mass is close to the present accelerator bound, it would no longer be relativistic as it diffuses out of the core. Such a neutrino of either helicity has significant mixtures of both chiralities, and hence is effectively trapped. Therefore, our bound applies to τ- neutrinos of masses less than a few MeV. In addition, we note that non-vanishing neutrino masses imply, in general, the existence of a mixing matrix analogous to the Kobayashi-Maskawa matrix in the quark sector. This leads to decay modes for neutrinos via mixing, and our bounds thus apply to unstable neutrinos with lifetimes greater than the diffusion time scale of several seconds.

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DISCUSSION

Q. **R. Svobaoda** *(Louisiana State Univ.)*: It would seem the experimental uncertainties exceed the theoretical ones in your limits on the mass of $m_\nu = \sqrt{m_\nu^2 + m_\tau^2} \leq 14$ keV. What is the major uncertainty in your calculation?

A. **R. Ghandi**: The equation of state is the biggest source of uncertainty. However, it is stressed that the limit derived is not sensitive to this to an appreciable extent.

Q. **V. A. Rubakov** *(INR, Moscow)*: You mentioned an order of magnitude uncertainty in your mass limit. Is this what you think of your calculations?

A. **R. Gandhi**: No. The order of magnitude is simply mentioned as a number that skeptics generally associate with astrophysical bounds on particle properties. The biggest uncertainty in our calculation stems from the imprecisely known equation of state, and as shown own limit is not very sensitive to this.