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NEUTRINOS FROM SN 1987A

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The simultaneous detection of neutrinos from the LMC supernova 1987A by the Kamiokande II and the Irvine-Michigan-Brookhaven (IMB) neutrino detectors can be considered an epochal event in stellar astronomy. The detection was simultaneous, (apart from some horological hairsplitting!) The first Kamioka event was at Feb. 23 7^h 35^m 35^s (± 1 min) UT while the first IMB event was clocked at Feb. 23 7^h 35^m 41.37s UT.

The detection of the neutrino burst a few hours before sighting of SN 1987A gave the first indication that the progenitor was a blue giant star rather than the canonical progenitor which is a red supergiant. That is, the outward shock speed of a few thousand kilometres per second x ($\approx 10^4$ secs) gives a propagation distance of a few times 10^{12} cm which is the typical size of a blue giant. Had the progenitor been a red supergiant there would have been a gap of three or four days between the detection of the neutrino event and the sighting of SN 1987A. Later on, the progenitor was indeed identified as a B3 supergiant Sanduleak -69 202.

The detection of the neutrinos confirms many aspects of the underlying phenomena of stellar collapse. The rapidly increasing density of the collapsing core makes it increasingly opaque to neutrinos, so that the characteristic neutrino emission time is not the hydrodynamic collapse time scale of a few milliseconds but rather the neutrino diffusion time which is a few seconds. The bulk of the binding energy of the neutron star formed is emitted in the form of neutrinos of all flavours. The total number of neutrinos spewed out by SN 1987A exceeded a collossal ten thousand septendecillion (ie. $> 10^{58}$) while over a period of ten seconds more than fifty octillion (5×10^{28}) neutrinos passed right through the Earth. More than hundred trillion neutrinos passed through each one of us! The total neutrino energy that impinged on earth corresponds to about half a kilogram of mass (i.e. $\approx 4 \times 10^{23}$ ergs). The average flux was about 5×10^{9} cm^{-2} sec^{-1}, which given the neutrino cross-sections ($\sim 10^{-43}$ cm^{2}) corresponds to an expected 5 to 10 events in water detectors of a few kilotons over a period of about ten seconds. Thus the neutrino detection from SN 1987A is consistent with that expected from a type II supernova (caused by the collapse of a massive star of a few solar masses) at the distance of LMC. It must be pointed out that in a type-I supernova canonically caused by carbon deflagration or detonation of a white dwarf about a solar mass of Ni^{56} is produced which decays into Fe^{56} finally in about eighty days each decay producing two neutrinos of a few MeV energy. Thus although the total neutrino energy is not much different, the neutrino flux would be about a million times less because the decay occurs over several days. Thus the neutrino flux from type I supernovae would be too little to be detectable! Now if the time scale of neutrino emission is the collapse (or free-fall) time scale, then the maximal ν luminosity would be : (R_{NC} = radius of nuclear core)

$$L_\nu \text{ (max)} \approx \frac{GM^2/R_{NC}}{t_{ff}}$$

Now $R_{NC} \approx 10$ km, $M \simeq M_\odot$

Then $t_{ff} \sim \frac{1}{(G\rho)^{1/2}} \sim 5 \text{ ms } \left(\frac{\rho}{10^{12} \text{ g cm}^{-3}}\right)^{1/2}$

$\therefore L_\nu(\text{max}) \simeq 10^{57}$ ergs/sec if there were no neutrino diffusion. This would imply the whole binding energy being emitted by neutrinos in time scales of a millisecond or less! However coherent neutrino scattering of nuclei of atomic mass A and atomic number Z (via $\nu + A \rightarrow \nu + A$ etc) considerably increases the cross-section and decreases the mean free path, leading to diffusion. The cross-section for coherent neutrino scattering goes as A^2 ; i.e.

$$\sigma_{A(Coh)} \simeq \left(\frac{\hbar}{m_e c}\right)^{-4} \left(\frac{G_F}{m_e c^2}\right)^2 \left(\frac{E_\nu}{m_e c^2}\right)^2 A^2 \left[1 - \frac{Z}{A} + (U \sin^2\theta_W - 1) \times \frac{Z}{A}\right]^2$$

E_ν is the neutrino energy. G_F is fermi constant, m_e is the electron rest mass. θ_W is the Weinberg angle.

The corresponding opacity for 10 MeV neutrinos scattering off iron is $\kappa_\nu \approx 10^{-17} \times 2\ cm^2\ gm^{-1}$, $\kappa_\nu = \sigma_{A\ Coh}/Am_p$ so that the actual neutrino luminosity of the collapsing core is:

$$L_\nu \simeq \frac{GM^2/R_{NC}}{t_d} ;$$

where t_d is the neutrino diffusion time

$$t_d \approx \frac{\lambda_{A\ Coh}}{C} N_{scatt} ; \quad \lambda_{A\ Coh}\ N^{1/2}_{Scatt} \sim R$$

$$1/\lambda_{A\ Coh} \simeq \left(\frac{\rho}{Am_p}\right) \sigma_{A(Coh)}. \qquad (m_p \text{ is proton mass}).$$

$\lambda_{A\ Coh}$ is the mean free path for coherent neutrino scattering and N_{scatt} is the number of scatterings while diffusing a distance R.

$t_d \approx 0.1 \left(\frac{\rho}{10^{12}}\right)$ S, so that for $\rho \simeq 10^{14}$ gm cm^{-3}, close to nuclear density (near core rebound). $t_d \approx 10$ secs implying that neutrinos take about ten seconds to diffuse out. For $\rho \approx 2 \times 10^{11}$ g/cc, $t_d \approx t_{FF}$. $L_{\nu\ actual} \approx 10^{52}$ ergs/sec to be compared with the corresponding neutrino. Eddington luminosity $L_\nu (Edd.) \approx \frac{4\pi GMC}{\kappa_\nu} \approx 10^{54}$ ergs/sec. Now when the core bounces around nuclear density, the neutrino fermi energy (which represents the average neutrino energy) is greater than 200 MeV.

But the neutrinos do not stream out at these high energies, due to neutrino trapping (the dense core is optically thick to neutrinos) and they are reduced in energy due to multiple scatterings (as is evident by use of the above formulae) and finally they escape with average energies of ~ 10 to 20 MeV! The Kamioka detection threshold was ~ 7 MeV and that of IMB somewhat higher. The fact that neutrinos were detected in the energy range 10 to 30 MeV (and not a few <u>hundred</u> MeV!) and over a time scale of a few seconds (and not <u>milliseconds</u>) provides strong support to the above picture of neutrinos diffusing out of a dense core and getting reduced in energy by multiple coherent scattering. In fact $\lambda_\nu \approx 10\ \mathrm{km} \left(\frac{10^{12}}{\rho\,(\mathrm{gm\ cm^{-3}})} \right) \left(\frac{10\ \mathrm{MeV}}{E_\nu} \right)^2 \alpha\ 1/E_\nu^2$

λ_ν (at bounce) $\approx 10^2$cm $R \approx 10^6$ cm $\therefore$ optical depth $\simeq 10^4$. The neutrino escape time can be written as sum of

$$t_\nu \approx \text{const.}\ \frac{R^2}{C\lambda^A_{coh}} + \text{const.}\ R/C$$

t_ν / t_{ff} goes as $\rho^{3/2}$ Neutral current processes dominate. DATA from the Kamioka and IMB detectors are given in Table. The eleven Kamioka events are clustered in three bunches. Setting $t = 0.0$ as the time of the first event, the first bunch consists of 5 events between 0.0 and ~ 0.5s; the second bunch of 3 events between 1.5 and 2.0 secs and the third of 3 events between 9.0 and 12.5 secs. The observed secondary electron energies as inferred from the emitted Cherenkov light range between 7.5 and 35 MeV, with errors of 20-25%. There are eight events concentrated within the first two seconds. The first two events are most probably due to electron-neutrino scattering $\nu_e + e^- \rightarrow \nu_e + e^-$, which sends electrons only in forward cone, the ν_e direction is not altered. The large angles of the other events due to antineutrino ($\bar{\nu}_e$) scattering of protons in the water detector. The reaction $\bar{\nu}_e + p \rightarrow n + e^+$, emits positrons ($e^+$) almost isotropically. The cross-section of this reaction is almost hundred times larger than that of the $\nu_e e$, scattering reactions. The directions of the events are random except for the first and second events. The neutrino burst detection thus began with the first two neutrino scattering events occuring within 107 ms. The direction of electrons produced by these two events is small from counter direction of LMC. The probability of e^+ being emitted within 20° in first event is 3% and therefore expected number is only 0.33 in eleven events.

Electron scattering by ν_e , ν_μ or ν_τ is only 1/5 to 1/7 the scattering cross-section of that of ν_e e. First two events may be due to initial neutronisation burst. That is, when the outgoing shock wave reaches densities of $\sim 10^{11}$ gm cm^{-3} after having started near 10^{14}gm cm^{-3}, the rapid capture of electrons by the newly liberated free protons ($e^- + p \rightarrow n + \nu_e$) can produce electron neutrinos that because of the lower densities can escape. This process can take away 1-2x10^{51} ergs within ten milliseconds and leads to the so called prompt neutronisation burst of neutrinos. The neutrino spectrum can be assumed to be a Fermi-Dirac distribution with temperature T and vanishing μ , i.e. F(E,T). Mean energy of flux $<E> = 3.15T$ and mean energy of the detected neutrinos is:

$$\bar{E} = \frac{\int_0^\infty E\sigma(E)\, f(E_e)\, F(E,T)dE}{\int_0^\infty \sigma(E) f(E_e)\, F(E,T)dE}$$

$f(E_e)$ = detection efficiency of positrons, $\sigma(E)$= C.S. Assuming that the neutrino luminosity given by: $L_\nu \sim GM^2/R_{NVC}/t_d$ is emitted as thermal neutrino radiation from surface of cooling core, the effective temperature of emission is given by:

$$L_\nu = (7/8\, N_\nu\, \sigma\, T^4_{eff})\ (4\pi R^2_{NVC})$$

$N_\nu = 6$ (i.e. three species of ν_e , ν_μ and ν_τ)and antiparticles. So that $< E_{\nu\ (escaping)} > = 3.15\ K\ T_{eff}$. ∴ .Total energy emitted by the hot neutron star is:

$$\int L_\nu\, dt = 2\, N_\nu\, F_0\ (3.15\ T_0)\ (4\pi D^2)\tau$$
$$= 6^{+2.5}_{-2.5} \times 10^{52}\ N_\nu\ (D/50\ kpc)^2 \text{ ergs.}$$

which is for a black-body model with $T_{eff} = T_0 = 4.5$ MeV and a cooling half-time of $\tau = 5s$, i.e.

$T = T_0 \exp(-t/2\tau)$

As the neutrino optical depth in the SN is large and density drops by several magnitudes at outer layers the ν spectrum is nearly thermal. It can probably be fitted with one temperature. Best fit temp. ≈ 3 MeV, $\tau = 5$ secs. For $N_\nu = 6$, the above formula gives a total energy emitted in neutrinos of all species of about 3×10^{53} ergs.

Both the Kamioka and IMB data allow us to determine the average energy of the emitted neutrinos, the effective temperature of the source and the total energy emitted in anti-neutrinos (as most of the events seen are due to anti-neutrinos as explained).

The relatively smaller number of events and imperfect energy resolution of both detectors introduce large uncertainties in the calculations. The large number of high-angle Kamioka events confirms predictions in usual models that the antineutrinos ($\bar{\nu}_e$'s) should dominate the signal. As a 'THUMB RULE', on average each 10 MeV $\bar{\nu}_e$ detection implies $\sim 4\times10^{51}$ ergs at LMC source each ν_e detection implies $\sim 5\times10^{52}$ ergs and each $\nu_\mu \sim 10^{53}$ ergs. ν_μ detection very unlikely. We must correct for energy dependence of cross-sections ($\bar{\nu}_e$-pαE_ν^2) and detector efficiencies $W(E)$. Average energy $\langle E_{\nu_d} \rangle$ of detected neutrinos is:

$$\langle E_{\nu_d} \rangle = \frac{\sum_i E_i}{N_d} = \frac{\int_H^\infty E^5 \, f\, W(E)dE}{\int_H^\infty E^4 \, f\, W(E)dE} = T \, \frac{G_5(H)}{a_4(H/T)}$$

H is the threshold energy E_i = energy of ith detected neutrino. The integrals are threshold truncated modified Fermi integrals. N_d = total number of detected neutrinos. Implicit function for T has to be solved. The expression for total energy flux in anti-neutrinos from SN 1987A turns out as:

$$E_{\bar{\nu}_e} = 0.8\times10^{52} \left(\frac{D}{50\text{kpc}}\right)^2 \left(\frac{1}{M}\right) \left[\frac{-F_3(0)\, G_5(H/T)}{G_4^2\,(H/T)}\right] \left[\frac{10\text{MeV}}{\langle E_{\nu_d}\rangle}\right] \times N_d \text{ ergs}$$

M = detector mass in Kilotons = 2 for Kamioka, 5 for IMB. For Kamioka, $\langle E \rangle$ for $\bar{\nu}_e$ is 8.5 MeV, and $E_{\bar{\nu}_e} = 5 \times 10^{52}$ ergs, $T_{eff} = 3.0$ MeV. $\therefore$ The total energy radiated in neutrinos of all species (E_{T_ν}) is $\approx 6 \times E_{\bar{\nu}_e} \approx 3 \times 10^{53}$ ergs. Scales with D^2. Similar figures are obtained for IMB. The total energy of $\sim 3 \times 10^{53}$ ergs in neutrinos corresponds to the gravitational binding energy of a 1.4 $M_\odot$ neutron star for realistic equations of state. It is gratifyingly close to that expected if a hot neutron star forms and cools by emitting mainly neutrinos.

Again this close agreement in energies implies that it is indeed the neutrinos and not any other exotic particles (like photinos, supersymmetric particles or axions) that carry away the bulk of the neutron star's binding energy. There is no need to invoke any of these exotic particles and in fact rather severe constraints can be placed on existence of such particles. Again the data does not prove any conjectures on the existence of different neutrino mass eigenstates or on their mixing. If the neutrino has a mass, spectrum of energies implies a spectrum of speeds. A δ-function pulse of neutrinos with a variety of energies would disperse as it travels the large distance between LMC and earth. The delay time is easily derived to be:

$\Delta t \simeq 2.5 \left(\frac{m}{10 eV}\right)^2 \left[\frac{10 MeV}{E_\nu}\right]^2$ secs. for an assumed distance of 50 Kpc. 10% uncertainty in distance, corresponds to 5% uncertainty in m. Observed spread of arrival times can be used to constrain neutrino mass. No compelling need on basis of data to evoke a neutrino mass, subject to electron energy errors one can however get an upper limit of < 6.5 eV. This implies that electron neutrinos cannot be the dominant dark matter constituent of galactic halos where phase space constraints require $m > 50$ eV. Severe constraints can also be placed on MSW parameters. MSW oscillations now appear doubtful in the range required for solving solar neutrino problem.

Limits can also be put on neutrino electric charge. Radius of curvature of trajectory (in metres) in intergalactic magnetic field:

$r = E/0.3\ Bq$. The arc $r\theta$ followed by neutrinos longer than straight path S, by $\delta s = r\theta - 2r \sin\theta/2 \approx \theta S\, \theta^2/24$ $\theta = S/r \ll 1$.

Thus $\delta S/S = 1/24 \dfrac{(0.3\ BSq)^2}{E_\nu^2}$

∴ Difference in length of trajectories of two neutrinos of average E differing by ΔE is:

$$\Delta S/S = \Delta t/t = 1/12 \frac{(0.3\ BSq)^2}{E^2} \frac{\Delta E}{E}$$

or $$q/e \leq \frac{12}{0.3} \frac{E}{BS} \left(\frac{\Delta t/t}{\Delta E/E}\right)^{1/2}$$

For LMC ν's, $E \approx 15$ MeV, $\Delta E/E = 1/2$, $\Delta t < 5s$

$B \approx 10^{-3}\ \mu G$ (intergalacticover $S = 50$ Kpc)

$B = 1\ \mu G$ (galactic over $S = 10$ Kpc)

$t = 1 \times 10^{12} s$.

∴ $q/e < 2 \times 10^{-17}$, e being the electron charge.

Stringent limits on the neutrino magnetic moment can also be placed. Neutrinos with magnetic moment (μ_ν) precess in external fields and extremely relativistic ν's from SN 1987A can flip helicities, i.e. finite neutrino magnetic moment can cause depolarisation of neutrinos crossing intergalactic distances. Rate at which the neutrinos flip helicities making them undetectable (i.e. left handed neutrinos precess into right handed ones under magnetic field) given by:

$$\Gamma_{LP} \approx \frac{2}{\pi} \frac{\mu_\nu .Bc}{h}, \quad \Gamma_{LP} = 1/t_\nu = 2 \times 10^{-13}\ S^{-1},$$

(requirement that the neutrinos do not flip on the way!). Thus detection of the SN 1987A neutrinos would constrain the neutrino magnetic moment to be:

$\mu_\nu < \Gamma_{LR}\ \pi h/2BC$ .Integrating over path lengths passing through intergalactic and galactic magnetic field gives $\mu_\nu < 10^{-20}$ μ_B, μ_B is the Bohr magneton. In Weinberg-Salam electroweak theory neutrinos can acquire magnetic moment of

$$\mu_\nu \approx 3eG_F\, m_\nu / 8\sqrt{2}\, \pi^2 C \simeq 3 \times 10^{-19} \mu_B \left(\frac{m_\nu}{1eV}\right)$$

∴ the SN 1987A limit on μ_ν is consistent with this. It rules out the large value of $10^{-10}\mu_B$, required by the Vysotski-Voloshin-Okun (VVO) mechanism to explain solar neutrino anticorrelation with solar activity. Also constraints particle physics models which give large μ_ν. Again it must be pointed out that all supernova explosions since the beginning would have given rise to a faint diffuse anti-neutrino background (of mean energy ~ a few MeV) of about 50 to 100 cm^{-2} sec^{-1}. The $\bar{\nu}_e$ background produced by the 325 nuclear power stations (fission reactors) with average power output ~ 200 Gigawatts is also ~ 60 cm^{-2} sec^{-1} (mean energy ~ 5 MeV) which is the same as the total supernova antineutrino background! Thus ν-astronomy in some energy range is already swamped or jammed by artificial sources.

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