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Limits to the Radiative Decays of Neutrinos and Axions from γ-ray Observations of SN 1987A

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Abstract. Using γ-ray observations made by the Solar Maximum Mission Gamma Ray Spectrometer in the energy range 4.1 – 6.4 MeV we limit the possible radiative decays of neutrinos and axions emitted by SN 1987A. For neutrinos less massive than about 20 eV our constraint is $\tau_\nu/m_\nu \gtrsim 1.7 \times 10^{15} B_\gamma$ sec/eV; and for masses between 20 and 275 eV our constraint is $\tau_\nu \gtrsim 3.4 \times 10^{16} B_\gamma \gamma_{\rm GRS}^{-1/2}$ sec, where B_γ is the branching ratio for the radiative decay mode and $\gamma_{\rm GRS}$ is the yet undetermined instrument background count rate in units of 0.1 sec^{-1}. The first limit is some 2 orders-or-magnitude better than the previous limit based upon the integrated γ-ray flux from all supernovae. The axion limit is less interesting: $m_a \lesssim 55\gamma_{\rm GRS}^{11/94}$ eV.

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The neutrino burst observations of the Kamiokande-II detector (KII)[1] and the Irvine-Michigan-Brookhaven detector (IMB)[2] confirm the general picture of a type II supernova: the *ca.* 3×10^{53} ergs of binding energy released when the *ca.* $1.4 M_\odot$ core of a massive star collapses to form a neutron star is carried off in thermal neutrinos (of all species) with a temperature of $T_\nu \simeq 4$ MeV.[3] If one or more of the neutrino species is massive (but light enough to be produced by the supernova, $m_\nu \lesssim$ *few* MeV) and unstable with a radiative decay mode, then the decay of neutrinos of that species will produce copious numbers of γ rays. Cowsik[4] exploited this fact to place a constraint to the radiative decay modes of massive neutrino species. He calculated the integrated flux of γ rays resulting from the decay of neutrinos produced by all type II supernovae throughout the history of the Universe, insisted that it be less than the measured γ-ray backgound flux at energies of order 10 MeV, and obtained the limit $\tau_\nu / m_\nu \gtrsim 3 \times 10^{16}$sec/eV valid for neutrino masses less than a few MeV (and assuming that the branching ratio to radiative modes is unity). We will show that a more realistic estimate of the limit using Cowsik's method gives a bound that is more than 3 orders-of-magnitude *less* stringent.

Decaying neutrinos from SN 1987A should produce γ rays of energy $\langle E_\gamma \rangle \simeq E_\nu/2 \simeq 3T_\nu/2 \simeq 6$ MeV. Fortunately, there were several γ-ray detectors operating around the time of the supernova. The most sensitive for our purposes, the Gamma Ray Spectrometer (GRS) instrument on board the Solar Maximum Mission (SMM),[5] did not detect a signal above normal instrument background in the $4.1 - 6.4$ MeV energy range during a 10 sec time interval following the detection of the neutrinos by KII and IMB. Using the *direct* observational bound in this energy band, we set a limit to the masses and lifetimes of unstable neutrinos, which for $m_\nu \lesssim 20$ eV is 2 orders-of-magnitude more stringent than the limit obtained by Cowsik's method, and up to 10 orders-of-magnitude more stringent than the limit based upon the fact that the $\bar{\nu}_e$'s did not decay in flight.[1,2] Our bound to the radiative decay of neutrinos is the most sensitive limit in the mass range $m_\nu \lesssim 0.1$ eV. For a summary of other astrophysical and cosmological bounds to neutrino mass and lifetime we refer the reader to Ref. 6.

The GRS is a multicrystal scintillation spectrometer which is sensitive to γ rays in the energy range 0.3-100 MeV, and has an energy dependent effective area of order 10^2cm^2 (for a complete description of the GRS see Ref. 5). The SMM spacecraft and the GRS instrument axis always point toward the sun, while the direction to the Large Magellanic Cloud (LMC) is roughly orthogonal to the plane of the ecliptic. When the spacecraft is in the 'zero-roll' position (along the satellite-sun rotation axis) it nonetheless has significant sensitivity to γ rays from the direction of the LMC. Fortunately, during and after the neutrino burst from SN 1987A the spacecraft was in the zero-roll position with a minimum of obscuring material. During the 10 sec time interval in which IMB detected neutrinos from SN 1987A, the SMM-GRS detector did not detect a γ-ray signal above normal instrument background in the energy range 0.3-100 MeV; based upon this they set a 3σ upper limit to the fluence of γ rays in the $4.1 - 6.4$ MeV energy range during that period:[7] $f_\gamma \lesssim 1$ cm^{-2}.

During the *ca.* 1500 sec time interval following the IMB neutrino burst, the SMM-GRS detector was also operational and there was no obvious signal above normal background;[7] however, a fluence limit for this time interval has yet to be reported. If we assume that there was no signal and that the instrument background rate $\Gamma_{\rm GRS}$ was roughly constant during the period 10 sec $\lesssim \Delta t \lesssim$ 1500 sec (here, 'roughly' means constant to within a factor of a few), then the corresponding fluence limit for time intervals Δt in the range

10 sec $\lesssim \Delta t \lesssim$ 1500 sec is $f_\gamma \lesssim 0.3(\gamma_{\rm GRS}\Delta t/{\rm sec})^{1/2}$ cm^{-2}, where $\gamma_{\rm GRS} \equiv \Gamma_{GRS}/0.1\,{\rm s}^{-1}$ is expected to be of order unity. After Δt =1500 sec, the spectrometer was in a low power mode.

The distance to SN1987A is $d_{\rm LMC} \simeq$ 55 kpc = 1.7×10^{23}cm, which corresponds to a light-travel time $t_{\rm LMC} = 5.7 \times 10^{12}$sec. Since the decaying neutrino species is massive, it does not travel with $v = c$, and the daughter photons will arrive somewhat later than a massless neutrino species. For purposes of arrival time, the $\bar{\nu}_e$'s detected by IMB can be treated as a massless neutrino species with no appreciable time delay.[8] The time delay and spread in the arrival time of the γ-ray pulse is determined by the mass of the parent neutrino. If the parent neutrino has a mass m_ν, γ rays would arrive later than the $\bar{\nu}_e$'s and would have a spread in arrival times, both characterized by $\Delta t \simeq (t_{\rm LMC})(m_\nu^2/E_\nu^2)/2 \simeq 0.02 m_{\rm eV}^2$ sec (using $\langle E_\nu \rangle$ = 12 MeV). We will take the spread in arrival time of the γ-ray pulse to be of this order. For neutrino masses less than about 20 eV, the spread of the γ-ray pulse is less than or of order 10 sec, and in this mass range the SMM-GRS fluence limit for the 10 sec interval when the IMB neutrino pulse was detected provides the appropriate upper limit to the γ-ray fluence produced by neutrino decays. For neutrino masses 20eV $\lesssim m_\nu \lesssim$ 275 eV, the decay-produced γ-ray burst would have arrived within the window 10 sec $\lesssim \Delta t \lesssim$ 1500 sec, and the relevant γ-ray fluence limit is then $f_\gamma \lesssim 0.3(\gamma_{\rm GRS}\Delta t/{\rm sec})^{1/2}{\rm cm}^{-2}$. Using the previous relation between Δt and m_ν, the fluence limit depends upon the mass of the neutrino as $f_\gamma \lesssim 0.05\gamma_{\rm GRS}^{1/2} m_{\rm eV}$ cm^{-2}, for $m_\nu \gtrsim$ 20 eV. To summarize then, we will use the γ-ray fluence limits

$$f_\gamma \lesssim 1 \text{ cm}^{-2} \qquad [m_\nu \lesssim 20 \text{ eV}] \tag{1a}$$

$$f_\gamma \lesssim 0.05\gamma_{\rm GRS}^{1/2} m_{\rm eV} \text{ cm}^{-2} \qquad [20 \text{ eV} \lesssim m_\nu \lesssim 275 \text{ eV}] \tag{1b}$$

What γ-ray fluence is expected from decaying neutrinos emitted by SN 1987A? Consistent with the neutrino bursts detected by KII and IMB, we assume a simple model of neutrino emission from the supernova: *ca.* 10^{53} ergs per neutrino species characterized by a temperature of *ca.* 4 MeV.[3] This implies $N_{\nu\bar{\nu}} \simeq 5.2 \times 10^{57}$ neutrinos and antineutrinos of each species were produced by the supernova, and using a supernova distance of 55 kpc, this results in a neutrino fluence per species of $f_{\nu\bar{\nu}} \simeq 1.4 \times 10^{10}$ cm^{-2}. We note that this neutrino plus antineutrino fluence is consistent with the $\bar{\nu}_e$ fluence inferred by KII, $f_{\bar{\nu}_e} \sim 10^{10}$ cm^{-2} (Ref. 1). Also notice that the $\nu\bar{\nu}$ fluence is some 10 orders-of-magnitude greater than the γ-ray fluence limits; roughly speaking then, only 1 in 10^{10} neutrinos could have decayed producing a γ.[7]

The γ-ray fluence in the 4.1-6.4 MeV energy band from the decay of neutrinos of a given species is given by $f_\gamma = f_{\nu\bar{\nu}} W_\gamma B_\gamma [1 - \exp(-t_{\rm LMC} m_\nu/\langle E_\nu \rangle \tau_\nu)]$, where $\langle E_\nu \rangle \simeq 12$ MeV is the average energy per neutrino, B_γ is the branching ratio to the radiative mode ($\nu_i \to \nu_j + \gamma$), and W_γ is the fraction of decay photons in the 4.1-6.4 MeV energy range. This expression simplifies in the limit that the 'lab' lifetime of the neutrino ($\tau_\nu \langle E_\nu \rangle / m_\nu$) is either much greater or much less than $t_{\rm LMC}$. The 'lab' lifetime is equal to $t_{\rm LMC}$ if $\tau_{\rm sec}/m_{\rm eV} = 4.7 \times 10^5$, where $m_{\rm eV}$ is the neutrino mass in eV, and $\tau_{\rm sec}$ is the neutrino lifetime in sec. To summarize, the γ-ray flux expected from the decay of neutrinos of a given species is

$$f_\gamma \simeq f_{\nu\bar{\nu}} W_\gamma \, B_\gamma \, \frac{t_{\rm LMC} m_\nu}{\tau_\nu \langle E_\nu \rangle} = 6.8 \times 10^{15} \; W_\gamma B_\gamma \; m_{\rm eV}/\tau_{\rm sec} \text{ cm}^{-2} \qquad [\frac{\tau_{\rm sec}}{m_{\rm eV}} \gtrsim 4.7 \times 10^5] \tag{2a}$$

$$f_\gamma \simeq f_{\nu\bar\nu}\, W_\gamma B_\gamma = 1.4\times10^{10} W_\gamma B_\gamma \ \mathrm{cm}^{-2} \qquad [\frac{\tau_{\rm sec}}{m_{\rm eV}} \lesssim 4.7\times10^5]. \tag{2b}$$

If the neutrino flux is blackbody with a temperature of 4 MeV and if the daughter photon has half the incident neutrino energy, then $W_\gamma = 0.25$. Using this value for W_γ and requiring that the γ-ray fluence calculated in Eq.(2) is less than the limit provided by Eq.(1) yields constraints to the lifetime if $\tau_{\rm sec}/m_{\rm eV} \gtrsim 4.7\times10^5$:

$$\tau_\nu \gtrsim 1.7\times10^{15}\ m_{\rm eV} B_\gamma \ \mathrm{sec} \qquad m_\nu \lesssim 20\mathrm{eV} \tag{3a}$$

$$\tau_\nu \gtrsim 3.4\times10^{16} B_\gamma \gamma_{\rm GRS}^{-1/2}\ \mathrm{sec} \qquad 20\ \mathrm{eV} \lesssim m_\nu \lesssim 275\ \mathrm{eV}, \tag{3b}$$

and constraints to the branching ratio if $\tau_{\rm sec}/m_{\rm eV} \lesssim 4.7\times10^5$:

$$B_\gamma \lesssim 2.8\times10^{-10} \qquad m_\nu \lesssim 20\mathrm{eV} \tag{4a}$$

$$B_\gamma \lesssim 1.4\times10^{-11}\gamma_{\rm GRS}^{1/2} m_{\rm eV} \qquad 20\ \mathrm{eV} \lesssim m_\nu \lesssim 275\ \mathrm{eV}. \tag{4b}$$

It has been noted that the observation of $\bar\nu_e$'s by KII and IMB imply that the 'lab' lifetime of the $\bar\nu_e$ must be greater than $t_{\rm LMC}$, or $\tau_\nu \gtrsim 4.7\times10^5 m_{\rm eV}$ sec (see, e.g., Ref. 1). Our method improves this limit by a factor of $10^{10}B_\gamma$. The origin of this factor is easy to see: the limit to the γ-ray fluence is about a factor of 10^{10} less than the $\nu\bar\nu$ fluence,[7] and B_γ accounts for the fraction of decays that produce a gamma.

Apparently, the neutrino mass-lifetime bound based upon γ-ray observations of SN 1987A is not as stringent as the number derived by Cowsik—of course, it is a *direct*, as opposed to *indirect* bound. This issue led us to reexamine Cowsik's bound, and we found it to be overly restrictive by about 3 orders-of-magnitude! We now rederive the bound based upon Cowsik's method. Let n_γ be the present number density of γ rays from decays of supernova-produced neutrinos and antineutrinos throughout the history of the Universe. Then the present flux of such γ rays is just $F_\gamma = n_\gamma c/4\pi$. The number density of supernova produced γ's is (assuming the 'lab' neutrino lifetime is longer than the age of the Universe)

$$n_\gamma = N_{\nu\bar\nu} B_\gamma \frac{m_\nu}{\langle E_\nu\rangle \tau_\nu}\int_0^{t_U} \Gamma_{\rm SN}(t)(t_U - t)dt, \tag{5}$$

where $t_U = t_{10}10^{10}$ yrs is the age of the Universe and $\Gamma_{\rm SN}(t)$ is the type II supernova rate (per cm^3 per sec). Using the estimated type II rate for our own galaxy, ~ 1 supernova per 30 yrs per $10^{11}M_\odot$ of baryons (see Tammann in Ref. 9), it follows that $\Gamma_{SN}(\mathrm{today}) = 10^{-84}(\Omega_B h^2/0.01)\mathrm{cm}^{-3}\mathrm{s}^{-1}$, where, as usual, the present Hubble parameter is $100h$ km s^{-1}Mpc^{-1}. In addition, primordial nucleosynthesis restricts $\Omega_B h^2$ to be less than 0.035 (Ref. 10). A type II rate of $1.1h^2$ per 100 yrs per $10^{10}L_{B\odot}$ was derived from a recent 5 yr supernova search of $\sim$ 1000 galaxies (see van den Bergh, et al. in Ref. 9). Using the mean luminosity density of the Universe, $\sim 2.4h\times10^8 L_{B\odot}\mathrm{Mpc}^{-3}$, this translates to $\Gamma_{SN}(\mathrm{today}) = 2.5h^3\times10^{-85}\mathrm{cm}^{-3}\mathrm{s}^{-1}$. Note that these two estimates differ by a factor of $\sim 4(\Omega_B h^2/0.01)h^{-3}$.

Taking the supernova rate to be constant throughout the history of the Universe, and equal to an intermediate value, $\Gamma_{SN}(t) = 10^{-84}\mathrm{cm}^{-3}\mathrm{s}^{-1}$, it follows that

$$F_\gamma \simeq 5\times10^{10} B_\gamma(\Gamma_{SN}/10^{-84}\mathrm{cm}^{-3}\mathrm{s}^{-1})t_{10}^2\frac{m_{\rm eV}}{\tau_{\rm sec}}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}. \tag{6}$$

The average energy of these γ rays today is: $\langle E_\gamma \rangle \simeq (3T/2)/\langle 1+z_{SN}\rangle \simeq 6\,\mathrm{MeV}/\langle 1+z_{SN}\rangle$, where z_{SN} is the average redshift of the supernova produced γ's, probably of the order of a few. Comparing this flux with the measured γ-ray background flux for $E_\gamma \simeq 1-3$ MeV, $F_\gamma \simeq 3\times 10^{-3}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$, we derive the limit:

$$\tau_\nu \gtrsim 1\times 10^{13}\ m_{eV} B_\gamma (\Gamma_{SN}/10^{-84}\mathrm{cm}^{-3}\mathrm{s}^{-1}) t_{10}^2 \ \mathrm{sec}, \quad (7)$$

which is more than 3 orders-of-magnitude weaker than that derived by Cowsik. The discrepancy traces to a missing 4π, an assumed age of the Universe of 32 Gyr, assuming all the supernova energy is radiated in one neutrino species, *etc*, but not, however, to the assumed type II rate. [Cowsik[4] derives a similar limit based upon X-ray emission from white dwarfs; careful scrutiny also weakens this bound by a similar amount. In addition, $\nu_\mu\bar{\nu}_\mu$ and $\nu_\tau\bar{\nu}_\tau$ emission from cooling white dwarfs is greatly suppressed relative to $\nu_e\bar{\nu}_e$ emission since these species are only produced by neutral current processes.]

To summarize the comparison between the SN 1987A bound and that based upon the integrated γ-ray flux from all supernovae, we can say that the SN 1987A bound is both more stringent and more direct. However, the latter bound is valid for neutrino masses as large as a few MeV; recall, however, stronger bounds exist for $m_\nu \gtrsim 0.1$ eV.[6] Our method and Cowsik's method assume the neutrinos decay in flight, outside the expanding star. Since the progenitor of SN 1987A had a radius $R \lesssim 3\times 10^{12}$ cm, the $\nu\bar{\nu}$'s would have decayed within the exploding blue supergiant if $\tau_\nu \lesssim 8\times 10^{-6} m_{eV}$ sec, and our bounds would not apply. However, in this case other bounds apply.[11] And of course, the observation of $\bar{\nu}_e$'s by KII and IMB preclude their decay inside the progenitor. Finally, we note that limits to the radiative decay of heavy ($m_\nu \gtrsim$ *few* MeV) neutrinos have been found by methods similar to ours.[12]

It has been pointed out that axions more massive than about 3 eV (if they exist) should have been emitted from SN 1987A with acceptable luminosity[13]. Their emission is characterized by:

$$T_a \simeq 15(m_a/\mathrm{eV})^{-4/11}\mathrm{MeV}, \quad (8a)$$

$$Q_a \simeq 1.5\times 10^{54}(m_a/\mathrm{eV})^{-16/11}\mathrm{ergs}, \quad (8b)$$

$$N_a \simeq Q_a/3T_a \simeq 2.1\times 10^{58}(m_a/\mathrm{eV})^{-12/11}. \quad (8c)$$

From this it follows that the axion fluence is $f_a \simeq 5.7\times 10^{10}(m_a/\mathrm{eV})^{-12/11}\mathrm{cm}^{-2}$, and that the γ-ray fluence in the 4.1-6.4 MeV range from axion decays ($a \to 2\gamma$) is $f_\gamma = 2W_\gamma f_a(m_a/\langle E_a\rangle)(t_{\mathrm{LMC}}/\tau_a)$. Taking the axion lifetime to be $\tau_a \simeq 6\times 10^{24}(m_a/\mathrm{eV})^{-5}$sec, we find (again using $W_\gamma = 0.25$)

$$f_\gamma \simeq 1.8\times 10^{-9}(m_a/\mathrm{eV})^{58/11}\mathrm{cm}^{-2}. \quad (9)$$

Using the SMM-GRS 3σ limit to the γ-ray fluence for time intervals longer than 10 sec, we obtain the bound $m_a \lesssim 55\gamma_{\mathrm{GRS}}^{11/94}$eV. However, the radiative decays of relic axions from the early Universe already precludes axion masses greater than about 3-5 eV,[14] and axion emission from red giants precludes axion masses greater than about 30-40 eV.[15] [The corresponding limit to the axion mass from the integrated flux of all type II supernovae is about a factor of 2-3 less stringent than the SMM-GRS bound.]

Finally, we mention that γ-ray detectors on the Japanese Ginga X-ray satellite, and on the Pioneer Venus Orbiter were also operating at the time the neutrino pulse from SN 1987A arrived. However, their constraints to the γ-ray fluence are far less restrictive.

To summarize our results, using the SMM-GRS γ-ray observations of SN 1987A we have placed a very restrictive bound to the mass and lifetime of any unstable neutrino species with a radiative decay branch: $\tau_\nu/m_\nu \gtrsim 1.7\times10^{15}B_\gamma$ sec/eV, for $m_\nu \lesssim 20$ eV; and $\tau_\nu \gtrsim 3.4\times10^{16}B_\gamma\gamma_{\rm GRS}^{-1/2}$ sec, for $20 \lesssim m_\nu \lesssim 275$ eV. Our limits are both based upon direct observations of a type II supernova and more 2 orders-of-magnitude more stringent than the previous limit set by Cowsik's method. While we have no direct evidence that axions were radiated from SN 1987A (or for that matter that axions even exist), based upon theoretical calculations they should have been. The same SMM-GRS observations also constrain the axion mass (assuming the model for axion emission in Ref. 13): $m_a \lesssim 55\gamma_{\rm GRS}^{11/94}$ eV, a limit which is less interesting.

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type II rate, which may not be indicative of the average rate over the history of the Universe. One can also think of several reasons why the core collapse rate might be higher than these estimates. Although type Ib supernovae lack H lines, they too may result from the core collapses of massive stars which have shed their H envelopes. The observed type Ib rate is $\sim \frac{1}{2}$ of the type II rate. SN 1987A was 2-3 magnitudes less luminous (at maximum brightness) than the 'standard type II', presumably due to the small size of its blue supergiant progenitor. The rates derived from supernova searches necessarily depend upon the assumed light curve and maximum brightness, and if SN 1987A is representative of a significant class of supernovae, type II rates may have to be revised upward.

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