Axions and SN 1987A

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We consider the effect of free-streaming axion emission on numerical models for the cooling of the newly born neutron star associated with SN 1987A. We find that for an axion mass of greater than $\sim 10^{-3}$ eV, axion emission shortens the duration of the expected neutrino burst so significantly that it would be inconsistent with the neutrino observations made by the Kamiokande II and Irvine-Michigan-Brookhaven detectors. However, we have not investigated the possibility that axion trapping (which should occur for masses ≥ 0.02 eV) sufficiently reduces axion emission so that axion masses greater than ~ 2 eV would be consistent with the neutrino observations.

I. INTRODUCTION

SN 1987A confirmed astrophysicists' most cherished beliefs about the nature of type-II supernovae: that they are associated with the formation of neutron stars and that in the process they release their binding energy in thermal neutrinos.[1] In addition, it has also provided a wealth of information about the properties of neutrinos and other hypothetical, weakly interacting particles. In particular, the detection of 11 neutrino events over ~ 12 sec by the Kamiokande II (KII) detector[2] and 8 neutrino events over ~ 6 sec by the Irvine-Michigan-Brookhaven (IMB) detector[3] indicates that thermal neutrinos with temperature ~ 4 MeV indeed carried away the bulk of the $\sim (2-4)\times 10^{53}$ ergs of binding energy from the explosion.[1] In turn, these observations have led to constraints to the mass, charge, unknown interactions, magnetic moment, speed of propagation, and lifetime of the electron antineutrino, on the possible existence of right-handed neutrinos and their coupling strength, and on the possible existence and mass of the axion.[4-8] It is the last of these issues which we will address in this paper.

The axion was proposed in 1977 to solve the strong *CP* problem of quantum chromodynamics[9] (QCD). To date, it is still the most attractive solution to this solitary blemish on QCD. The axion necessarily couples to nucleons, with a strength proportional to its mass, and may also couple to electrons (though it need not). Astrophysical arguments (red giant emission) preclude an axion of mass greater than ~ 0.01 eV [Dine-Fischler-Srednicki- (DFS-) type axion[10]] or $\sim 2-30$ eV (hadronic-type axion),[11] while the cosmological production of axions precludes an axion of mass less than a few $\times 10^{-6}$ eV (Ref. 12). Thus, there exists a window of allowed axion masses: few$\times 10^{-6}$ eV to 2–30 eV (hadronic-type axion) or few$\times 10^{-6}$ eV to 10^{-2} eV (DFS-type axion).

For axion masses in this window, axion emission by nucleon-nucleon axion bremsstrahlung from the newly born neutron star associated with SN 1987A should have been a significant cooling mechanism. If the axion exists, such a heat sink would have accelerated the cooling and thereby shortened the duration of the neutrino signal that was detected by the KII and IMB detectors. With neutrino cooling alone, theoretical protoneutron star models predicted that the neutrino burst would last for on the order of several to many seconds[13]— not inconsistent with the observations. Several groups of authors[4-8] have argued that an axion with mass in the range $(10^{-3}-2.0)$ eV is ruled out, as, for such a mass, axion emission would be so important that it would drastically reduce the duration of the neutrino burst. (For axion masses less than ~ 0.02 eV, axions freely stream out of the core; for masses greater than ~ 0.02 eV, axions become trapped and are radiated from the "axion sphere;"[4] and for axion masses greater than ~ 2 eV, trapping apparently renders axion emission insignificant.[4])

The purpose of this paper is to address in a very quantitative way the axion mass limit in the free-streaming regime ($m_a \leq 0.02$ eV); in a later work we plan to address the trapped regime ($m_a \geq 0.02$ eV). In particular, while previous authors have used axion emission rates that are valid in either the strongly degenerate regime or the nondegenerate regime, here we use rates which are valid for arbitrary nucleon degeneracy.[5] Not all previous work has incorporated the back reaction of axion cooling on the model of the cooling neutron star (an effect which is expected to be important[6]), and in none of the previous work has the effect of axion emission on the observed neutrino bursts been quantitatively addressed. In this work we fully and self-consistently incorporate axion emission into the model for the cooling of the young neutron star, and calculate the expected response of the KII and IMB detectors to the resulting neutrino flux (number of events, burst duration, and "visible" neutrino energy). To derive a limit to the axion mass we use the expected duration of the detected neutrino burst in the KII and IMB detectors. Because of uncertainties in both the equation of state at supranuclear densities and the actual baryon mass of the remnant, we explore a variety of numerical models[14] to test the sensitivity of our limit to the theoretical models of the nascent neutron star employed (and find that this sensitivity is rather insignificant).

As alluded to above and as expected, the observable most sensitive to axion cooling is the duration of the neutrino burst. For the wide range of models we have explored, axion emission has virtually no effect on the burst duration if the axion mass is less than or equal to 10^{-4} eV. However, if the axion mass is greater than or equal to 10^{-2} eV, the duration of the neutrino bursts in both detectors for all models considered is less than 1 sec. Such a short time is clearly in conflict with the observations. For all the models we considered, the neutrino burst duration dropped precipitously at an axion mass of 10^{-3} eV, strongly suggesting that the upper limit to the axion mass (in the free-streaming regime) is 10^{-3} eV (to within approximately a factor of 2).

The paper is organized as follows. In Sec. II we describe the numerical models we use to simulate neutron-star cooling and to compute the expected neutrino signals in the KII and IMB detectors; in Sec. III we discuss the axion and the axion emission rates we use; in Sec. IV we describe the effect of axion emission on the cooling of the nascent neutron star associated with SN 1987A and on the expected neutrino signals; we end with a discussion and a summary in Sec. V, where, among other things, we address the uncertainties associated with our limit.

II. DESCRIPTION OF THE NUMERICAL CODE AND MODELS

For the purposes of this study, the protoneutron star evolution code of Burrows and Lattimer[13] and Burrows[14] was modified to include the axion energy-loss rates recently derived by Brinkmann and Turner[5] and described below in Sec. III. The code uses standard relaxation techniques to solve the general-relativistic equations of stellar structure. It incorporates all relevant red-shift factors, follows all six neutrino species (three two-component neutrino and antineutrino species), employs a "realistic" nuclear equation of states[13,14] (EOS), and has a sophisticated neutrino opacity algorithm. The neutrinos are assumed to be thermalized with the local matter temperature and to be emitted with a Fermi-Dirac energy distribution.

The core of a massive star becomes unstable upon reaching the Chandrasekhar mass ($\sim 1.4 M_\odot$) and implodes. Core collapse proceeds through 5 orders of magnitude in central density and 2 orders of magnitude in radius, and is halted only when the matter stiffens upon reaching nuclear densities. The inner core rebounds into the outer core, a shock wave is formed, and the inner structure, the protoneutron star, rapidly achieves hydrostatic equilibrium. It is during the quasihydrostatic neutronization and cooling phase (time scale $\sim$ seconds) of the protoneutron star, not during the dynamical phase of collapse and shock-wave formation (time scale $\sim$ milliseconds) that the prodigious neutron-star gravitational binding energy ($\sim 2-4\times 10^{53}$ ergs) is released. In the standard model, the energy is radiated as neutrinos (and antineutrinos) of all species. These protoneutron star neutrinos constitute the signature of "core collapse" (cf., Ref. 14) that was apparently detected by the KII[2] and IMB[3] detectors. At the high densities and temperatures typical of a nascent neutron star, even neutrino mean-free-paths (λ_ν) are small compared to the size of the core. Therefore, neutrino cooling proceeds on a long "diffusion" time scale (seconds) and not on the short production or light-travel time scales ($\ll$ second). Hence, the neutrino signal is spread over many seconds. The neutrino signal can be separated into two phases. The first is an outer mantle cooling phase, powered in part by residual accretion and quasistatic mantle collapse during the first 1–2 sec. The second phase is a later, longer (>2 sec) phase of inner core cooling during which the neutrino luminosity is powered by neutrino transport of energy from the core, characterized by the longer neutrino diffusion time scale (several sec). During both phases, the neutrinos escape from the periphery at the "neutrinosphere" where $\lambda_\nu \sim R$ (radius of the neutron star ~ 10 km). Because the capture process ($\bar{\nu}_e + p \rightarrow n + e^+$) has a much larger cross section than the various scattering processes ($\nu_i + e^- \rightarrow \nu_i + e^-$), the neutrino signal is dominated in H_2O detectors by its $\bar{\nu}_e$ component. In H_2O Cherenkov detectors, the secondary positron (or electron for a scattering process) is detected by its Cherenkov light. As has been pointed out by many analyses now,[1] the IMB and KII detections are consistent with an effective $\bar{\nu}_e$ temperature ($T_{\bar{\nu}_e}$) of ~ 4.0 MeV, a characteristic cooling time of ~ 4 sec, and a total binding energy ($6\times E_{\bar{\nu}_e}$) of $\sim 2-3\times 10^{53}$ ergs, all consistent with the standard model of a type-II supernova. However, if the axion exists and has a large mass (m_a), and therefore a large coupling, the resulting axion energy losses would be at the expense of neutrino emission, and the signal in neutrino detectors would be altered. In this paper we investigate the implications of axion emission for the predicted signals in IMB and KII. In most of the previous work, authors have used the results of standard numerical models (*without axion emission*), i.e., temperature and density profiles, to compute axion emission. However, to properly take account of the feedback on the temperature-dependent axion emission of the axion-cooling induced temperature decreases, a detailed evolutionary calculation, which incorporates axion emission *ab initio* is required. By doing so, one can then sensibly address the question: For what range of axion masses could we not fit the SN 1987A neutrino data?

Three protoneutron star models from the more comprehensive work of Burrows[14] were evolved at six different axion masses between 0.0 eV and 10^{-2} eV for 20 "physical" sec after bounce. In addition, it was assumed that axions once produced freely stream out—a valid assumption for $m_a \leq 0.02$ eV (Ref. 4). Using the published detector fiducial masses, efficiencies and energy thresholds, the appropriate neutrino interaction cross sections, and a supernova distance of 50 kpc, the predicted neutrino signals in both KII and IMB from SN 1987A were calculated. The effect on this signal of axion emission will be described in Sec. IV. The models (A, B, and C) were chosen to represent a range of possibilities, since the precise neutron star EOS and the ultimate baryon mass (M_B) of the residue are not accurately known. The initial entropy and lepton profiles employed were similar to those found in the collapse literature.[14] Model A is model 57 from Ref. 14, which starts at $M_B = 1.3\ M_\odot$ and accretes to a large $1.8\ M_\odot$ by means of an accretion rate that is taken to decay exponentially with a time constant of 0.5 sec. The EOS employed in model A is stiff, as described in Ref. 14. Similarly, model B is the stiff model 55 of Ref. 14, in which an initial core of mass $1.3\ M_\odot$ accretes to a mass of $1.5\ M_\odot$ with a similar accretion time constant. Model C is the soft model 62 from Ref. 14 that in all ways, save stiffness, is the same as model B. A soft calculation with baryon mass parameters similar to those of model A is not included in the set because the maximum baryon mass for the soft EOS is so small ($1.6\ M_\odot$) that a black hole would form early on (<1 sec), truncating the neutrino emission. With models A, B, and C, we represent a range of realistic behavior and binding energies of the protoneutron star.

III. THE AXION AND AXION EMISSION RATES

The axion is the hypothetical pseudo-Nambu-Goldstone boson associated with the spontaneous breakdown of the Peccei-Quinn quasisymmetry.[9] Peccei-Quinn (PQ) symmetry was proposed in 1977 to solve the "strong CP problem," that is, the violation of CP symmetry in QCD by nonperturbative, instanton effects. The mass of the axion is determined by the PQ symmetry-breaking scale f_a:

$$m_a \simeq (0.62 \text{ eV})\ [10^7 \text{ GeV}/(f_a/N)]\ , \tag{1}$$

where N is the color anomaly of the PQ symmetry.[16] Generically, there are two types of axions: axions that couple to both quarks and leptons, with strength $\sim m/f_a$ (m = quark or lepton mass), the so-called DFS-type axion;[17] and axions that couple only to quarks, and perhaps not even to the ordinary light quarks, but only to heavy, exotic quarks, the so-called hadronic-type axion.[18] Both types of axions couple to photons, gluons, and nucleons through electromagnetic and color anomalies.

The relevant couplings of both types of axions to electrons, photons, and nucleons are summarized in Ref. 4, and discussed in detail in Ref. 16. For the purposes at hand we are only interested in the axion-nucleon couplings, as by far the dominant axion emission process from SN 1987A is nucleon-nucleon, axion bremsstrahlung.[8] Those couplings, as computed in the naive quark model, are[4]

$$\begin{aligned} g_{an} &= [(X_d'/N - X_u'/4N) - 0.20]m/(f_a/N) \\ &\simeq 1.5\times 10^{-7}[(X_d'/N - X_u'/4N) \\ &\qquad - 0.20](m_a/\text{eV})\ , \end{aligned} \tag{2a}$$

$$\begin{aligned} g_{ap} &= [(X_u'/N - X_d'/4N) - 0.55]m/(f_a/N) \\ &\simeq 1.5\times 10^{-7}[(X_u'/N - X_d'/4N) \\ &\qquad - 0.55](m_a/\text{eV})\ , \end{aligned} \tag{2b}$$

where X_d' and X_u' are the PQ changes of the up and down quarks, m is the nucleon mass, and the interaction Lagrangian (with nucleons) is

$$\begin{aligned} \mathcal{L}_{\text{int}} = \cdots &+ (g_{an}/2m)(\bar{n}\gamma_\mu\gamma_5 n)\partial^\mu a \\ &+ (g_{ap}/2m)(\bar{p}\gamma_\mu\gamma_5 p)\partial^\mu a\ . \end{aligned} \tag{3}$$

The axion-nucleon coupling arises in roughly equal amounts from two sources: the direct coupling of the axion to up and down quarks (reflected in X_u' and X_d') and axion-pion mixing. For this reason, the axion-nucleon coupling is of the order or $m/(f_a/N)$, whether the axion is of the hadronic or of the DFS type. For comparison, the hadronic axion-electron coupling, which arises due only to radiative corrections, is some 4 orders of magnitude smaller than that of a DFS axion.

In the one-pion-exchange (OPE) approximation, there are eight (four direct and four exchange) Feynman diagrams for nucleon-nucleon axion bremsstrahlung, which are shown in Fig. 1. The matrix element squared for this process has been computed by Brinkmann and Turner,[5] by Kang,[19] and in the degenerate limit for the process $nn \to nn + a$ by Iwamoto.[20] In the nonrelativistic limit (i.e., to lowest order in $T/m \sim \text{few}\times 0.01$), the matrix element squared is constant and is given by[5]

$$\sum_{\text{spin}} |\mathcal{M}|^2 = \frac{256}{3}\frac{g_{an}^2 f^4 m^2}{m_\pi^4}(3-\beta) \tag{4}$$

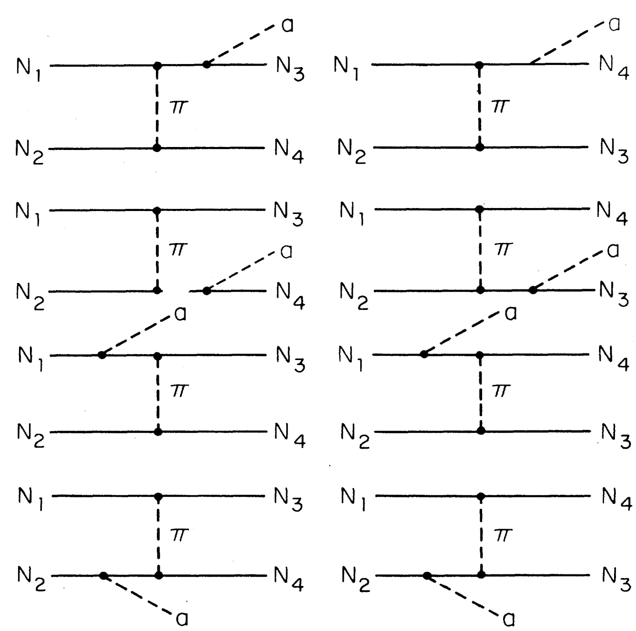

FIG. 1. Feynman diagrams for nucleon-nucleon, axion bremsstrahlung.

for the process $nn \to nn + a$, by

$$\sum_{\text{spin}} |\mathcal{M}|^2 = \frac{256}{3} \frac{g_{ap}^2 f^4 m^2}{m_\pi^4} (3-\beta) \quad (5)$$

for the process $pp \to pp + a$, and by

$$\sum_{\text{spin}} |\mathcal{M}|^2 = \frac{256 f^4 m^2}{3 m_\pi^4} \left[\frac{g_{an}+g_{ap}}{2} \right]^2 (2-4\beta/3) + \frac{256 f^4 m^2}{3 m_\pi^4} \left[\frac{g_{an}^2+g_{ap}^2}{2} \right] (5-2\beta/3) \quad (6)$$

for the process $np \to np + a$. Here $f \simeq 1.05$ is the neutral pion-neutron dimensionless coupling, and $\beta \equiv 3\langle (\hat{\mathbf{k}}\cdot\hat{\mathbf{l}})^2 \rangle$ is the phase-space weighted average of the spatial dot product between the direction of the three-momentum transfer in the direct and exchange diagrams: in the degenerate limit ($p_F^2/2m \gtrsim 3T$, or $T \lesssim 20$ MeV) $\beta \to 0$, while in the nondegenerate limit, $\beta \to 1.0845$. For complete details of the calculation of the matrix element squared, see Ref. 5.

The axion emission rate (energy per volume per time) is given by a 15-dimensional phase-space integral:

$$\dot{\mathcal{E}}_a = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_a (2\pi)^4 S \sum_{\text{spin}} |\mathcal{M}|^2 \delta^{(4)}(p_1+p_2-p_3-p_4-p_a) E_a f_1 f_2 (1-f_3)(1-f_4) , \quad (7)$$

where $d\Pi_i = d^3p_i/(2\pi)^3 2E_i$ is the Lorentz-invariant phase-space element, the labels $i = 1-4$ denote the incoming (1,2) and outgoing (3,4) nucleons, the label $i = a$ denotes the axion, and S is the usual symmetry factor for identical particles in the initial and final states ($S = 1$ for $np \to np + a$; $S = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ for $nn \to nn + a$, or $pp \to pp + a$). The nucleon phase-space distribution functions f_i are given by $f_i = [\exp(E_i/T - \mu_i/T) + 1]^{-1}$. Under the assumption that the matrix element squared is constant (which is accurate to about 10–20 %), Brinkmann and Turner[5] have evaluated this 15-dimensional integral numerically. Summing over all three bremsstrahlung process, they find

$$\dot{\mathcal{E}}_a = 64 (m^{2.5} T^{6.5} / m_\pi^4) f^4 \left[(1-\beta/3) g_{ab}^2 I(y_1,y_1) + (1-\beta/3) g_{ap}^2 I(y_2,y_2) + \frac{4(15-2\beta)}{9} \left[\frac{g_{an}^2+g_{ap}^2}{2} \right] I(y_1,y_2) + \frac{4(6-4\beta)}{9} \left[\frac{g_{ab}+g_{ap}}{2} \right]^2 I(y_1,y_2) \right] , \quad (8)$$

where the first term accounts for $nn \to nn + a$, the second term $pp \to pp + a$, and the third and fourth for $np \to np + a$. The quantities $y_1 = \mu_n/T$ and $y_2 = \mu_p/T$, where μ_n and μ_p are the chemical potentials of the neutron and proton. The quantity $I(y_1,y_2)$ is a three-dimensional integral that must and has been evaluated numerically. A convenient analytical expression (accurate to better than 25%) and a "look-up table" (accurate to better than 5%) are given in Ref. 5.

To compute $\dot{\mathcal{E}}_a$ one must specify g_{an}, g_{ap}, and β. The axion-nucleon couplings g_{an} and g_{ap} are obviously model dependent, and β depends upon the degree of degeneracy. For definiteness, as well as simplicity, we will take

$$g_{an} = g_{ap} = \frac{0.5m}{f_a/N} \simeq 7.6 \times 10^{-8} (m_a/\text{eV}) \quad (9)$$

and $\beta = \frac{1}{2}$. Given the other uncertainties inherent to this problem, and the fact that any axion mass limits derived scale only as $\dot{\mathcal{E}}_a^{1/2}$, these simplifications seem well justified. In any case, a more specific treatment is always possible. We should also emphasize that although we will state our results in terms of an axion mass limit, what we are actually placing limits on are g_{an}, g_{ap}: $m_a \lesssim 10^{-3}$ eV corresponds to $g_{an} = g_{ap} \lesssim 8 \times 10^{-11}$.

IV. THE EFFECT OF AXION COOLING ON THE SN 1987A NEUTRINO SIGNAL

The results from the 18 model calculations of this study ((models A, B, and C)$\times$[m_a(eV)=0.0, 10^{-4}, 3×10^{-4}, 10^{-3}, 3×10^{-3}, 10^{-2}]) are summarized in Figs. 2–6 and Table I. Figure 2 depicts the dependence of both the total energy lost to all species of neutrinos (E_ν) and the total axion energy loss (E_a) as a function of m_a for models A, B, and C. (Note: "total energy" here denotes the energy carried off in the first 20 sec; by 20 sec, the total energy has essentially converged.) Although the calculations were performed for only six values of m_a, continuous curves based upon interpolation are presented. As Fig. 2 demonstrates, for low values of m_a, E_ν falls in the range of reasonable neutron-star binding energies and only gradually decreases with increasing m_a. For all models, E_ν and E_a begin to respond to increasing m_a near $\sim 3\times10^{-4}$ eV, but only very gradually. Even for $m_a = 10^{-2}$ eV, E_a is only 45%, 56%, and 69% of E_ν at $m_a = 0.0$ eV for models A, B, and C, respectively. This sluggish dependence of E_a on m_a is a consequence of the feedback of axion cooling on the axion losses themselves. The axion emission rate varies as $\rho^2 T^{3.5}$ (nondegenerate limit) or $\rho^{1/3} T^6$ (degenerate limit); and because of this temperature/density dependence, axion emission is most significant deep in the core, which, as mentioned earlier, holds only about $\frac{1}{2}$ the heat released in the formation of the neutron star. Because of the stiff temperature dependence, axion emission is self-quenching, and, further, because the core only contains $\sim\frac{1}{2}$ the heat, the total axion losses amount to only $\sim\frac{1}{2}$ the total binding energy. As a result, a factor-of-10 increase in m_a from 10^{-3} eV to 10^{-2} eV, which without feedback would imply a factor-of-100 increase in axion energy losses ($\propto m_a^2$), actually results in increase factors

TABLE I. Summary of collapse models with axion emission.

m_a(eV)	Number of events expected KII	IMB	Emitted energy (10^{51} ergs) Axions	Neutrinos	Δt(90%) (sec) KII	IMB	Duration of calculations (sec)
			Model A (1.3→1.8$M_\odot$, stiff)				
0.0	15.28	6.74	0.0	328.1	9.0	4.0	20
10^{-4}	15.09	6.67	0.1	324.8	9.0	4.0	20
3×10^{-4}	14.89	6.63	14.7	319.3	8.0	3.5	20
10^{-3}	13.00	6.10	77.0	277.0	4.0	1.6	20
3×10^{-3}	11.30	5.51	121.6	238.3	1.6	1.0	20
10^{-2}	9.59	4.62	147.2	215.5	1.0	0.5	14
			Model B (1.3→1.5$M_\odot$, stiff)				
0.0	11.16	5.45	0.0	228.4	9.5	4.5	20
10^{-4}	11.11	5.37	2.6	226.8	9.5	4.3	20
3×10^{-4}	10.95	5.37	7.6	224.0	9.2	4.1	20
10^{-3}	9.65	4.97	45.3	195.2	6.0	2.6	20
3×10^{-3}	7.73	4.35	94.9	150.5	2.4	1.2	20
10^{-2}	6.17	3.96	127.6	118.5	1.0	0.6	18
			Model C (1.3→1.5$M_\odot$, soft)				
0.0	11.63	5.84	0.0	229.8	11.0	5.7	20
10^{-4}	11.62	5.84	7.2	229.2	11.0	5.7	20
3×10^{-4}	11.03	5.64	36.8	217.0	9.1	4.8	20
10^{-3}	9.13	5.02	99.6	176.3	4.3	2.0	20
3×10^{-3}	7.53	4.44	139.6	141.5	1.8	1.0	20
10^{-2}	6.40	3.82	159.1	122.2	1.0	0.5	10

of 1.9, 2.8, and 1.6 for models A, B, and C, respectively. The lethargy of (E_a, E_ν) vs m_a is also reflected in Fig. 3, which shows the slow decrease of N_K and N_I, the expected $\bar{\nu}_e$ event total in KII and IMB, respectively, for all three models. By $m_a=10^{-2}$ eV, the predicted event totals (N_i's) have decreased less than 50%. Based upon E_ν or the number of neutrino events, one would be hard pressed to rule out an axion as massive as 10^{-2} eV.

However, as Fig. 4 indicates, the neutrino signal durations in the IMB and KII detectors *are* sensitively decreasing functions of m_a beyond $\sim 3\times10^{-3}$ eV. In Fig. 4, $\Delta t(90\%)$, the time it takes the accumulated number of events to reach 90% of the final total number of events, is plotted as a function of m_a (90% of the final total is an arbitrary choice; similar behavior would follow for the choice of 60% or 70%). By $m_a \sim 10^{-3}$ eV, $\Delta t(90\%)$ has plummeted to values inconsistent with the long duration of the KII and IMB detections, and for $m_a=10^{-2}$ eV, the pulse duration for both detectors of all models is less than 1 sec. The cause of this can be traced as follows. The early phase of neutrino emission results from the initial heat in the outer mantle and accretion, and has a short time scale (~ 1 sec) because both neutrino diffusion in the low density, outer mantle, and residual accretion are rapid (<1 sec). The residual heat of the inner core is transported by neutrino diffusion to the outer core and the neutrinosphere on a time scale of several seconds, and thereby powers the late time neutrino flux. If the inner core heat source did not compensate for the quicker

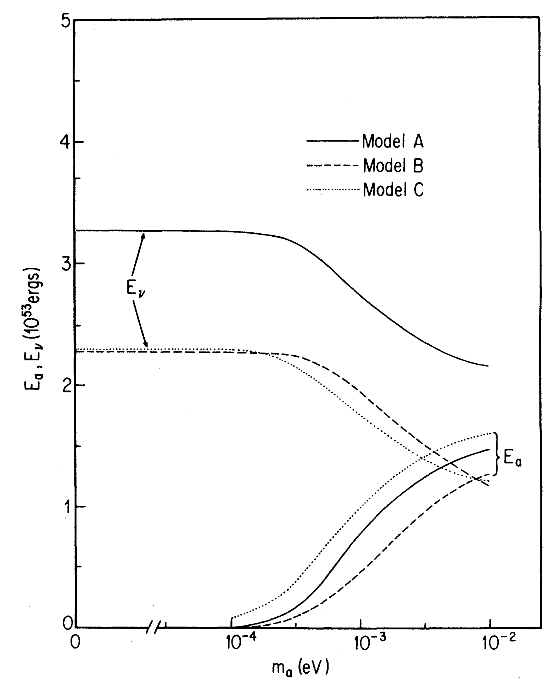

FIG. 2. The total neutrino energy (E_ν) and the total axion energy (E_a) lost (after 20 sec) vs axion mass m_a for models A (solid), B (dashed), and C (dotted). The energies are in units of 10^{53} ergs and m_a is in eV.

outer core losses, the temperature of the neutrinosphere (e.g., $T_{\bar{\nu}_e}$ for $\bar{\nu}_e$'s) and the neutrino luminosities would dive after ~ 1 sec and the neutrino flux would shut off. For $m_a = 0.0$ eV, the early, short phase smoothly merges into the later, long phase that accounts for $\sim \frac{1}{2}$ of the signal.[14] However, the major effect of axion emission is the cooling of this high-density inner core crucial to powering the second phase. As m_a approaches 10^{-3} eV, the core is rapidly depleted of heat and cannot supply the energy for the second phase. To illustrate this effect, the time evolution of the matter temperature profiles $[T(M)]$ for model A for $m_a = 0.0$ eV and $m_a = 10^{-2}$ eV are depicted in Figs. 5 and 6, respectively. Each curve represents a snapshot in time. The lowest curve is the initial profile. As the shock-puffed outer core settles from $R = 10^2$ km to $R = 10$ km, the resulting compression raises the temperature of the outer core dramatically. Subsequent accretion further compresses the protoneutron star, and temperatures near ~ 50 MeV are achieved. Such high temperatures are of course not manifested directly in the neutrino signals, since the neutrinosphere is located on the periphery where $T \sim 3-5$ MeV. In both Figs. 5 and 6, the snapshots are every 100 msec for the first 2.0 sec and then every 2.0 sec until the end ($t = 20.0$ sec). The large temperature spike in Fig. 5 drives a neutrino flux into the center, thereby raising its temperature and storing heat for phase two. In Fig. 6 it is plain to see that efficient axion cooling has refrigerated the inner core completely and depleted the heat reservoir for phase two.

The behavior of $\Delta t(90\%)$ in Fig. 4 echoes the above-described phenomenon. For instance, at $m_a = 10^{-2}$ eV in model A, $T_{\bar{\nu}_e}$, instead of being ~ 4.0 MeV at $t = 1.0$ sec, is a tepid ~ 2.5 MeV. In model A, at $m_a = 10^{-3}$ eV, $\Delta t(90\%)$ for IMB is only 40% of its $m_a = 0.0$-eV value and at $m_a = 10^{-2}$ eV, it is only $\sim 13\%$ of that value. Since the $m_a = 0.0$-eV models fit the IMB and KII detec-

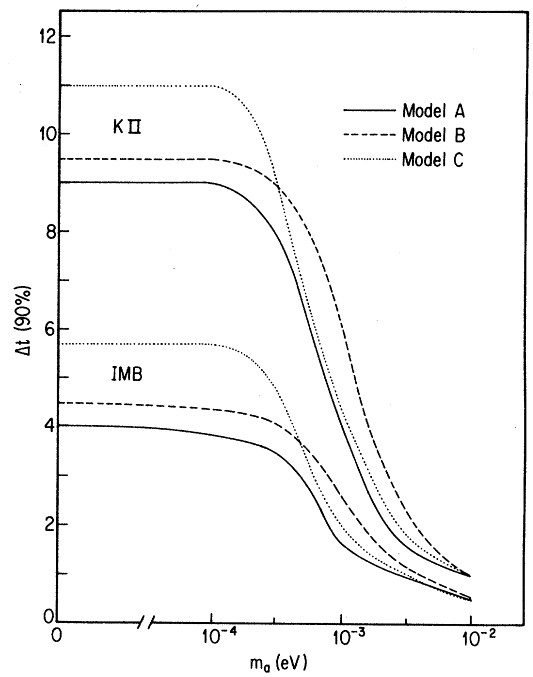

FIG. 4. The time required to accumulate 90% of the total number of expected $\bar{\nu}_e$ capture events, $\Delta t(90\%)$, in sec, vs the axion mass m_a in eV for the IMB and the KII detectors for models A (solid), B (dashed), and C (dotted). Note the precipitous drop in $\Delta t(90\%)$ at $m_a \sim 10^{-3}$ eV.

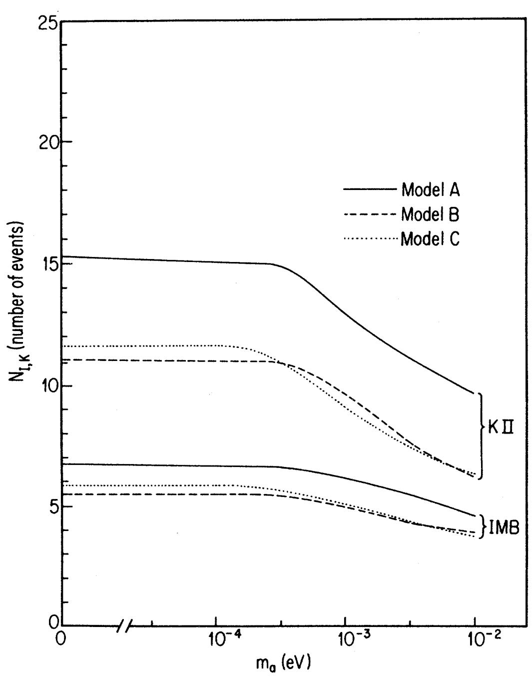

FIG. 3. The total expected number of $\bar{\nu}_e$ capture events (after 20 sec) in the IMB detector (N_I) and the KII (N_K) vs the axion mass, in eV. Models A, B, and C are the solid, dashed, and dotted curves, respectively.

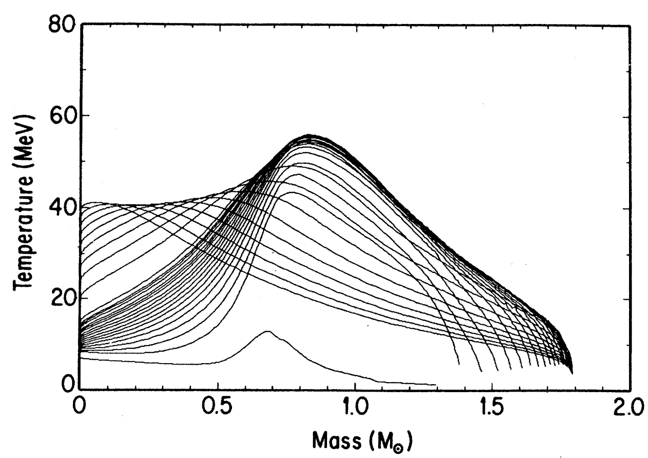

FIG. 5. Shapshots of the matter temperature (T) in MeV vs enclosed baryon mass (M) in solar masses for model A without axion emission. The initial model ($t = 0$) is the bottom curve. The snapshots are every 100 msec for the first 2 sec and then every 2 sec until the end (20 sec). The compression spike can be seen to first grow, then diffuse into the center, and finally begin to decay after most of this energy has diffused to the neutrinosphere and is radiated away.

tions, Fig. 4 strongly suggests an upper limit to m_a of 10^{-3} eV based on signal duration alone.

V. DISCUSSION AND SUMMARY

We have fully incorporated axion emission (in the free-streaming limit) into numerical models of the initial cooling of the newly born neutron star associated with SN 1987A. The dominant process for axion emission is nucleon-nucleon, axion bremsstrahlung, and our rates for this process are taken from Ref. 5, where the matrix element for this process has been calculated exactly (in the OPE approximation) and the phase-space integrals have been evaluated numerically. Based upon the predicted neutrino flux from our models and the published detector response parameters for the KII and IMB detectors, we have calculated the expected characteristics of the neutrino pulses which would have been detected for axion masses of 0, 10^{-4} eV, 3×10^{-4} eV, 10^{-3} eV, 3×10^{-3} eV, and 10^{-2} eV. By comparing the expected characteristics of the neutrino pulses with the neutrino pulses that were actually detected, we have quantitatively addressed the question of which axion masses are consistent (or inconsistent) with the experimental data.

Of all the characteristics of the predicted neutrino pulses, which included total number of events, effective neutrino temperature, total energy carried off in neutrinos and pulse duration, pulse duration was most sensitively dependent upon the axion mass. In particular, for the range of cooling models considered, and an assumed axion mass of 10^{-2} eV, the predicted pulse duration in the KII detector was less than 1 sec and in the IMB detector was less than $\frac{1}{2}$ sec—both clearly in variance with the observations. On the other hand, for this axion mass, the energy carried off in neutrinos is still $\sim 50\%$ or more of the total binding energy and the expected number of events were $\sim 7-10$ for KII and ~ 5 for IMB—numbers that are not obviously inconsistent with the actual observations. The reason for this is simple. The extended duration of the neutrino burst is connected to the long time required for neutrino diffusion to carry the heat trapped in the core of the neutron star to the neutrinosphere; with the addition of axion cooling, free-streaming axions from the core can rapidly carry off this heat and thereby truncate the late-time part of the neutrino pulse.

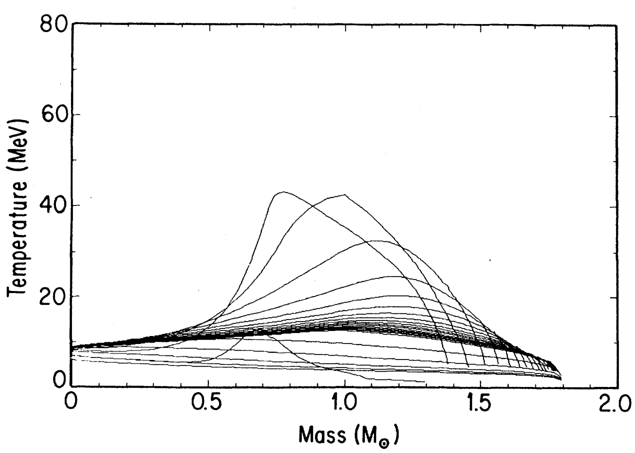

FIG. 6. Same as Fig. 5, but for $m_a = 10^{-2}$ eV. Note that axion cooling is so effective that the inner core never heats up, and thus the energy reservoir which should power the late-time neutrino emission does not exist.

While an axion mass of 10^{-2} eV is most certainly ruled out, models that incorporate an axion mass of 10^{-4} eV are virtually indistinguishable from those without axion cooling. From Fig. 4, where $\Delta t(90\%)$ is plotted vs axion mass, we see that for all cooling models the duration of the neutrino pulses has diminished dramatically for an axion mass of about 10^{-3} eV, to less than ~ 6 sec in the KII detector and to less than ~ 2.6 sec in the IMB detector. Moreover, for an axion mass of 3×10^{-3} eV, the predicted pulse durations are less than ~ 2.4 sec (KII) and ~ 1.2 (IMB). To summarize then, the neutrino detections made by the IMB and KII detectors most emphatically rule out an axion mass of 10^{-2} eV, most likely preclude an axion mass as large as 10^{-3} eV, and in no way preclude an axion mass as small as 10^{-4} eV, in agreement with the conclusions reached in Refs. 4–6 (also see Ref. 21).

We should mention the uncertainties associated with our analysis. First, we have relied upon purely theoretical models of the birth and initial cooling of the newly born neutron star associated with SN 1987A. Since the postcollapse densities are supranuclear, there is great uncertainty as to equation of state. In addition, there is the question of the efficiency of the shock at ejecting the outer mantle: how much material eventually rains back in on the neutron star? By considering a range of possible postcollapse models, we have tried to account for our ignorance, and, as Figs. 2–4 demonstrate, our conclusions are very robust and insensitive to the detailed collapse model. For all the models considered, the neutrino burst duration decreases dramatically around 10^{-3} eV (Ref. 22).

Perhaps more important are the uncertainties associated with the axion emission rate itself. Within the *assumptions* (the one-pion-exchange approximation), the emission rate has been computed quite accurately to better than 20%. However, one must question the validity of the OPE approximation in general: diagrams involving two-pion and other meson exchanges may be important.[22] In particular, Choi *et al.*[23] have recently suggested testing the validity of the OPE approximation by using OPE to compute the cross section for the related process, $pp \rightarrow pp\pi^0$, and comparing the result to experimental data (the point being that both the axion and pion are pseudo-Nambu-Goldstone bosons and, as such, both couple derivatively). Moreover, they claim that such a comparison indicates that OPE *overestimates* the cross section for this process by factors of 30–40 (Ref. 23). However, another similar and subsequent analysis[24] indicates that they have overestimated the discrepancy, and that the OPE calculation for $\sigma(pp \rightarrow pp\pi^0)$ agrees with the experimental data to better than a factor of 2. In addition, at supranuclear densities, collective nuclear effects, pion condensates, or quark matter in the core might modify the axion emission rate and the EOS. In this regard, we might recall that collective effects (plasma screening) modified the red giant bound to the mass of a DFS axion significantly.[10,25] It is somewhat reassuring, however, that the axion emission rate ($\dot{\mathcal{E}}_a$) is proportional to the axion mass squared. This then means that a factor-of-10 error in calculating $\dot{\mathcal{E}}_a$ translates into only a factor-of-3 error in any quoted axion mass limit.

In sum, in the free-streaming regime (axion masses ≤ 0.02 eV), we have shown that the existence of an axion more massive than $\sim 10^{-3}$ eV (more precisely, $g_{an} = g_{ap} \geq 8\times 10^{-11}$) would have resulted in neutrino pulses of unacceptably short duration in both the KII and IMB detectors. Because the axion-nucleon coupling is largely insensitive to whether the axion is hadronic or DFS, this result holds for both types of axions. For the hadronic axion, this improves the present mass constraint by about 3 orders of magnitude or more, while for the DFS axion, the improvement is only ~ 1 order of magnitude. Because of axion trapping, an axion more sensitive than ~ 2 eV is not expected to be precluded by the neutrino burst observations;[4] since other astrophysical arguments apparently preclude a DFS axion of this mass,[25] this is only relevant to the hadronic axion. While trapping only opens a relatively small window for the hadronic axion, it is a significant one, as an axion of that mass could be detected either by the cosmological decays of relic axions[26] or by a laboratory experiment.[27] Work to address the trapped regime ($m_a \geq 0.02$ eV) is in progress.

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[22]One might wonder if a severely shortened neutrino burst could be reconciled with the KII and IMB data if the neutrino burst were lengthened because of the dispersive effect of a nonzero neutrino mass. Raffelt and Seckel (Ref. 6) considered this possibly and concluded that it was unlikely because of the late arrival of neutrinos with high energy. Moreover, given the fact that the neutrinos detected by IMB have sufficiently high energies as to be relatively unaffected by a neutrino mass of $\sim$10–20 eV, we would conclude that the IMB data preclude this possible loophole.

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