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NEUTRINOS AND SUPERMASSIVE STARS: PROSPECTS FOR NEUTRINO EMISSION AND DETECTION

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ABSTRACT

We calculate the luminosity and energy spectrum of the neutrino emission from electron-positron pair annihilation during the collapse of a supermassive star ($M \gtrsim 5 \times 10^4\ M_\odot$). We then estimate the cumulative flux and energy spectrum of the resulting neutrino background as a function of the abundance and redshift of supermassive stars and the efficiency of these objects in converting gravitational energy into neutrino energy. We estimate the expected signal in some of the new generation of astrophysical neutrino detectors from both a cumulative background of supermassive stars and single collapse events associated with these objects.

Subject headings: elementary particles — stars: evolution — stars: formation — stars: interiors

1. INTRODUCTION

In this paper we examine the physics of neutrino emission in the collapse of supermassive stars. We also comment on the prospects for future terrestrial neutrino detectors to obtain a signal from these objects, and we discuss the possible consequences of such a signal for cosmology. By "supermassive stars" we mean stars so massive that they collapse on the general relativistic Feynman-Chandrasekhar instability. This will imply masses for these objects $M \gtrsim 5 \times 10^4\ M_\odot$ (see, for example, Fuller, Woosley, & Weaver 1986, hereafter FWW).

Although there is no direct evidence for the existence of these objects, we note that there is overwhelming evidence for the existence of supermassive black holes associated both with quasars and active galactic nuclei at high redshift and with almost every galaxy-sized structure examined appropriately by the *Hubble Space Telescope* (van der Marel et al. 1997). In turn, Begelman & Rees (1978) have shown that a supermassive star could result as an intermediate stage in the collapse of a relativistic star cluster to a black hole.

Alternatively, supermassive stars could have formed out of primordial clouds at high redshifts in which cooling was not as efficient as in clouds contaminated with metals (Hoyle & Fowler 1963; Bond, Arnett, & Carr 1984; FWW; McLaughlin & Fuller 1996). The typical baryonic Jeans mass at high redshift can be $\sim 10^5\ M_\odot$ (Peebles & Dicke 1968; Tegmark et al. 1997), but we do not know whether a cloud of this size would fragment into many pieces and form stars of smaller masses or collapse directly to form a large object. Given the relatively crude understanding we currently possess on star formation, it is interesting to explore the observational signatures of supermassive stars, one of which could be their neutrino emission during core collapse. (The other telltale signs of the existence and evolution history of supermassive stars could be the nucleosynthesis products of hot hydrogen burning [the rp-process; Wallace & Woosley 1981], greatly enhanced local helium and/or deuterium abundances [Woosley 1977; Fuller & Shi 1997], or the effects of large black holes.)

It would be very significant for our understanding of galaxy formation and cosmology if there were to be a new neutrino or nucleosynthesis probe of the epoch of galaxy/quasar formation at redshifts $z \sim 1$–5.

There are significant differences between neutrino emission in supermassive stars and in core-collapse supernovae. Neutrinos are trapped and thermalized in ordinary supernovae. Because of the different depths inside the supernova core where the various neutrino species thermally decouple, the average neutrino energies satisfy the hierarchy $E_{\nu_\tau} \approx E_{\bar{\nu}_\tau} \approx E_{\nu_\mu} \approx E_{\bar{\nu}_\mu} > E_{\bar{\nu}_e} > E_{\nu_e}$. By contrast, in supermassive stars neutrinos are produced principally by annihilation of thermal e^+e^- pairs. They can escape freely from the core, so their energy spectra are not thermal; different neutrino species will therefore have similar energy spectra.

The only known limit so far on the neutrino background from supermassive stars comes from the consideration that probably no more than $\sim O(0.1)$ of all baryons could ever have been in these objects, otherwise there would probably be too many $\sim 10^4$–$10^6\ M_\odot$ relic black holes. This limit is much less stringent than the limit on the supernova neutrino background. The supernova background limit can be obtained because the past and present supernova rates are subject to a very tight metallicity production constraint (Totani, Sato, & Yoshii 1996; Hartmann & Woosley 1997; Malaney 1997). The abundance of supermassive stars may not be subject to similar metallicity concerns, because these objects do not necessarily expel significant amounts of metals into the interstellar medium. However, while the supernova neutrino background has contributions from *recent* supernovae, the neutrino background from supermassive stars (if any) probably took its form at a higher redshift and therefore suffers a fair amount of redshift in energy. Consequently, although the relic neutrino flux of supermassive stars could be higher than the flux of relic supernova neutrinos, it has fewer neutrinos with energies in the range $\gtrsim 10$ MeV.

Numerical calculation of neutrino emissivity from e^+e^- annihilation have been carried out previously (Schinder et al. 1987; Itoh et al. 1989). In this paper we apply these results to the calculation of the neutrino luminosity and energy spectra in the collapse of supermassive stars. We then proceed to calculate the flux and energy spectrum of the neutrino background from a putative population of supermassive stars as a function of their abundance and redshift and of their efficiency in converting gravitational energy into neutrino energy. We estimate the event rate of this neutrino background in several new-generation neutrino detectors, including Super Kamiokande (Super K). We will also consider the expected event rate of a single neutrino burst from the collapse of a single supermassive star.

2. THE NEUTRINO LUMINOSITY FROM THE COLLAPSE OF A SUPERMASSIVE STAR

Fuller, Woosley, & Weaver (1986) have discussed the evolution and general relativistic instability of supermassive stars. In that work it was shown that these objects will most likely collapse into black holes unless the centrifugal force resulting from rapid rotation is strong enough to compensate the build-up of infall kinetic energy. During the collapse, only part of the star will plunge through the event horizon and become a "prompt" black hole. This is because the prodigious thermal neutrino pair emission will render the collapse of a nonrotating supermassive star nonhomologous (FWW; see also Goldreich & Weber 1980). Since supermassive stars have an index $n = 3$ polytropic structure and are dominated by radiation pressure P_r, the ratio of gas pressure P_g to the total pressure $P = P_r + P_g$ is

$$\frac{P_g}{P} \approx \frac{4.3}{\mu}\left(\frac{M_\odot}{M}\right)^{1/2} \quad (1)$$

(Weinberg 1972), where μ is the mean molecular weight ($\mu \approx 0.59$ for "primordial composition" of 75% hydrogen and 25% helium by mass), and M is the mass of the $n = 3$ polytrope. We also have $S_\gamma = 4(P_r/P_g)/3\mu \approx 4(P/P_g)/3\mu$, where S_γ is the photon entropy per baryon. Therefore the total entropy per baryon S is

$$S \approx (g/2)S_\gamma \approx 0.31(g/2)(M/M_\odot)^{1/2} , \quad (2)$$

where g is the statistical weight of relativistic particles. The relation between the initial stellar mass and the homologous core mass is then

$$\frac{M_5^{\rm HC}}{M_5^{\rm init}} \approx \sqrt{\frac{g^{\rm init}}{g^{\rm HC}}}\left(\frac{S^{\rm HC}}{S^{\rm init}}\right)^2 , \quad (3)$$

where superscript "init" always refers to quantities in the initial precollapse configuration, and superscript "HC" refers to quantities of the homologous core during the collapse. Here M_5 is the stellar mass in units of $10^5\ M_\odot$, $g^{\rm init} \approx 2$, and $g^{\rm HC} \approx 2 + (7/8) \times 4 = 5.5$. In the initial, nearly isentropic configuration, we have

$$S^{\rm init} \approx 0.93\left(\frac{M^{\rm init}}{M_\odot}\right)^{1/2} - \frac{4}{\mu} . \quad (4)$$

In equation (4) we have assumed that $g = 2$ and that all of the entropy is contributed by photons. This is an excellent approximation for a supermassive star near its general relativistic instability point.

As an example, if the entropy per baryon is reduced by a factor of 2.5 as a result of neutrino emission during the collapse, i.e., $S^{\rm HC}/S^{\rm init} \approx 0.4$, then the final homologous core mass will be about 10% of the initial stellar mass, $M_5^{\rm HC}/M_5^{\rm init} \approx 0.1$.

The total Newtonian gravitational binding energy of a homologous core with a mass $M_5^{\rm HC}$ is crudely $\sim E_s \approx 10^{59} M_5^{\rm HC}$ ergs. If there is no strong magnetic field present, most of this energy will be trapped inside the black hole, radiated through gravitational waves, or released by the neutrino emission prior to trapped-surface formation. The characteristic core radius near the black hole formation point is the Schwarzschild radius $r_S \approx 3 \times 10^{10} M_5^{\rm HC}$ cm. The characteristic duration of the collapse is the dynamic time $t_s \approx M_5^{\rm HC}$ s, or longer if rotation or magnetic fields hold up the collapse.

It has been shown that the neutrino energy loss rate per unit volume, Q, as a result of electron-positron annihilation, has the simple form

$$Q \approx 4 \times 10^{15} T_9^9 \text{ ergs cm}^{-3}\text{ s}^{-3} \quad (5)$$

(Schinder et al. 1987; Itoh et al. 1989), where $T_9 \equiv T/10^9$ K. This equation is valid so long as the temperature $T \gtrsim m_e$ (the electron rest mass) and as long as the density ρ is low enough to ensure nondegeneracy [$\rho \lesssim m_p T^3/\hbar^3 c^3 \sim 10^8 (T/1\text{ MeV})^3$ g cm^{-3}, where m_p is the proton rest mass]. Both conditions are satisfied during the collapse of a supermassive star. The neutrino luminosity from a supermassive star is then

$$L_\nu \approx \epsilon_1 \epsilon_2 \int_0^R 4\pi r^2 Q\, dr , \quad (6)$$

where R is the radius of the homologous core, ϵ_1 is a factor accounting for the travel time difference for neutrinos coming out from different depths inside the core (namely, to an outside inertial observer the neutrinos that originated deeper in the core were emitted earlier, when the core was larger and cooler), and ϵ_2 represents the effect of gravitational redshift.

During a homologous collapse, the density ρ has a self-similar profile of polytropic form:

$$\rho = \rho_c \theta_3^3(\xi) , \quad (7)$$

where ρ_c is the central density of the star, θ_3 is the index $n = 3$ Lane-Emden function, and $\xi = r/a$ is a dimensionless length measure. The total pressure at any point in the star can be cast in the index $n = 3$ polytropic form $P = K\rho^{4/3}$. Here the pressure constant can be expressed as

$$K \approx \frac{1}{4}\left(\frac{45}{2\pi^2}\right)\left(\frac{g}{g_{\rm S}}\right) g^{-1/3} S^{4/3}\left[1 + \frac{4}{\mu}\left(\frac{g_{\rm S}}{g}\right)\frac{1}{S}\right] N_{\rm A}^{4/3} , \quad (8)$$

where $N_{\rm A}$ is Avogadro's number and where $g_{\rm S}$ is the relativistic particle statistical weight entering into the entropy per baryon, $S \approx (2\pi^2 g_{\rm S} T^3/45)/\rho N_{\rm A}$. For all our considerations in this paper we can safely take $g_{\rm S} = g$. If we denote the density in units of 10^3 g cm^{-3} as ρ_3, then the pressure in units of MeV^4 will be $P = K_3 \rho_3^{4/3}$, with K_3 being

$$K_3 \approx (6.8 \times 10^{-6}\text{ MeV}^4)\left(\frac{11/2}{g_{\rm S}}\right)^{1/3} S_{100}^{4/3}\left(1 + \frac{0.04}{\mu S_{100}}\right) , \quad (9)$$

where S_{100} is the entropy per baryon, S, in units of 100 times Boltzmann's constant.

We can similarly estimate the dimensionless length conversion factor,

$$a = \frac{m_{\rm pl}}{\sqrt{\pi}} K^{1/2} \rho_c^{-1/3} \approx (8.2 \times 10^{10}\text{ cm})\left(\frac{11/2}{g_{\rm S}}\right)^{1/6} \times S_{100}^{2/3}\left(1 + \frac{0.04}{\mu S_{100}}\right)^{1/2}\left(\frac{\rho_c}{10^3\text{ g cm}^{-3}}\right)^{-1/3} , \quad (10)$$

where, in terms of Newton's constant G, the Planck mass is $m_{\rm pl} = G^{-1/2}$.

Because the entropy per baryon S_{100} is roughly constant throughout the radiation-dominated core at any time, we can estimate that $T_9^3/\rho_3 = 0.3S_{100} \approx$ constant (FWW). Therefore,

$$T \approx T_c\,\theta_3(\xi)\,, \tag{11}$$

and the quantity

$$T_9^{\rm aver} \approx (0.3S_{100}\,\bar\rho_3)^{1/3} \approx (0.3S_{100})^{1/3} \times \left(\frac{\int_0^R 4\pi r^2 \rho_3\,dr}{\int_0^R 4\pi r^2\,dr}\right)^{1/3} = \left(\frac{T_c}{10^9\ {\rm K}}\right)\left(\frac{\int_0^{\xi_1} \xi^2\theta_3^3\,d\xi}{\int_0^{\xi_1} \xi^2\,d\xi}\right)^{1/3}. \tag{12}$$

We take $T_9^{\rm aver}$ in this form for simplicity in calculating the average core density $\bar\rho$. The neutrino luminosity can then be expressed by integrating the Lane-Emden function,

$$\begin{aligned} L_\nu &\approx (4\times10^{15}\ {\rm ergs\ cm^{-3}\ s^{-1}})\epsilon_1\epsilon_2\left(\frac{T_c}{10^9\ {\rm K}}\right)^9(4\pi a^3) \times \int_0^{\xi_1}\xi^2\theta_3^9(\xi)d\xi \\ &= (4\times10^{15}\ {\rm ergs\ cm^{-3}\ s^{-1}})\epsilon_1\epsilon_2(T_9^{\rm aver})^9 \times \left(\frac{\int_0^{\xi_1}\xi^2\,d\xi}{\int_0^{\xi_1}\xi^2\theta_3^3\,d\xi}\right)^3(4\pi a^3)\int_0^{\xi_1}\theta_3^9(\xi)d\xi \\ &= (1.6\times10^{18}\ {\rm ergs\ cm^{-3}\ s^{-1}})\epsilon_1\,\epsilon_2(T_9^{\rm aver})^9\left(\frac{4\pi R^3}{3}\right). \end{aligned} \tag{13}$$

Apparently, most of the neutrinos are emitted near the black hole formation point, where $T_9^{\rm aver}$ is the highest. Therefore, to a good approximation we can take the radius of the core R to be $\beta r_{\rm S} \approx 3\times10^{10}\beta M_5^{\rm HC}$ cm where $\beta \gtrsim 1$, with a characteristic dynamic time of $\beta t_{\rm S} \approx \beta M_5^{\rm HC}$ s. The volume-averaged core density is $\bar\rho \approx M^{\rm HC}/(4\pi\beta^3 r_{\rm S}^3/3) = 1.83\times10^6\beta^{-3}(M_5^{\rm HC})^{-2}$ g cm^{-3}. On the other hand, the entropy per baryon in the homologous core (FWW) is

$$S_{100}^{\rm HC} = \alpha S_{100}^{\rm init} = 2.9\alpha(M_5^{\rm init})^{1/2} = 2.9\alpha(M_5^{\rm HC})^{1/2} \times (M_5^{\rm init}/M_5^{\rm HC})^{1/2}\,, \tag{14}$$

where $\alpha \equiv S_{100}^{\rm HC}/S_{100}^{\rm init}$, the factor by which the initial entropy is reduced by neutrino emission in the course of core collapse. Therefore, we conclude that

$$T_9^{\rm aver} = (0.3S_{100}\,\bar\rho_3)^{1/3} = 12\alpha^{1/3}\beta^{-1}\left(\frac{M_5^{\rm init}}{M_5^{\rm HC}}\right)^{1/6}(M_5^{\rm HC})^{-1/2}\,. \tag{15}$$

From equation (3) we find $\alpha^2(M_5^{\rm init}/M_5^{\rm HC}) \approx (5.5/2)^{-1/2} \approx 1.66$. Therefore, $T_9^{\rm aver} \approx 13(\beta^2 M_5^{\rm HC})^{-1/2}$. As a result, equation (13) becomes

$$L_\nu \approx 2\times10^{60}\epsilon_1\epsilon_2\,\beta^{-6}(M_5^{\rm HC})^{-1.5}\ {\rm ergs\ cm^{-3}\ s^{-1}}\,. \tag{16}$$

An accurate estimate of ϵ_1 and ϵ_2 requires a three-dimensional numerical treatment with full general relativity. Given all the other uncertainties inherent in the problem of supermassive star formation and collapse, it suffices in this paper to give a "ball park" estimate of these factors using the Newtonian picture. By assuming that all neutrinos are emitted in the positive radial direction (not a bad assumption, because most neutrinos are emitted from the central part of the core, as seen from Fig. 1) and that the neutrino emission from the core is cut off when $R = r_{\rm S}$, we estimate that $\epsilon_1 \approx 1/40$.

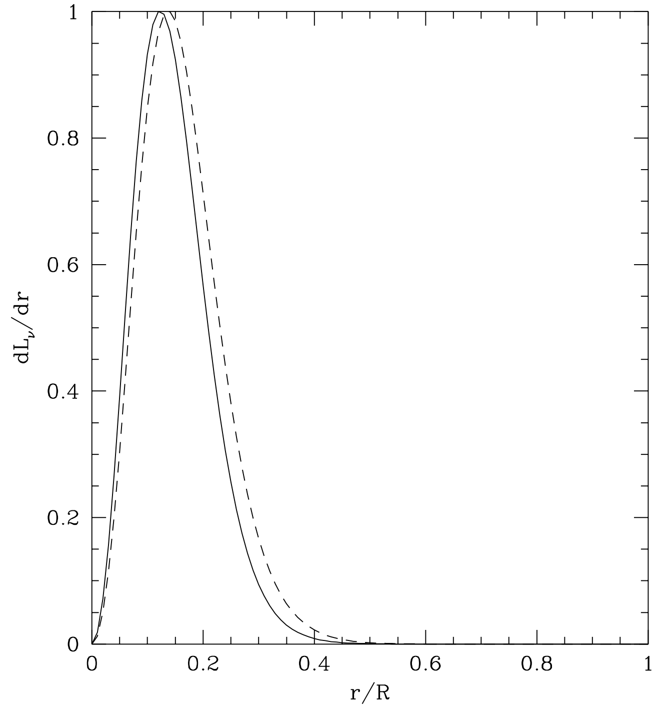

FIG. 1.—Neutrino production distribution inside the homologous core (unnormalized): the distribution when travel time differences are neglected (*solid curve*) and the distribution when travel time differences are considered (*dashed line*).

Estimating ϵ_2 is trickier. Because most neutrinos are from the central region of the core, neutrinos emerging from the core when the core radius is R are mostly emitted $\sim R/c$ earlier, when the core still has a radius of $\sim 2R$ and is less relativistic. We therefore apply the core-surface redshift factor $\epsilon_2 \sim 1 - r_{\rm S}/R = 1 - \beta^{-1}$ [a factor of $(1 - r_{\rm S}/R)^{-1/2}$ from energy redshift and an additional $(1 - r_{\rm S}/R)^{-1/2}$ from time dilation to observers] to all neutrinos. Although the Newtonian picture simply does not apply to the strong field and time-dependent situation, we believe that by applying the above ϵ_1 and ϵ_2 to equation (13), we can get a "ball park" estimate for the neutrino luminosity

$$L_\nu \sim 5\times10^{58}\beta^{-6}(1-\beta^{-1})(M_5^{\rm HC})^{-1.5}\ {\rm ergs\ cm^{-3}\ s^{-1}}\,. \tag{17}$$

The time evolution of the neutrino luminosity to an observer at infinity is shown in Figure 2, with $\beta(1-\beta^{-1})^{-1/2}$ crudely being the observer time axis if the core radius is collapsing at the speed of light. The peak luminosity is reached at $\beta \equiv R/r_{\rm S} \approx 7/6$. Integrating over time yields the total neutrino energy loss up to the formation of the black hole:

$$\begin{aligned} E_{\nu\,\rm loss} &\sim \int_1^\infty L_\nu\sqrt{1-\beta^{-1}}\,d(\beta t_{\rm S}) \\ &\sim 3.6\times10^{57}(M_5^{\rm HC})^{-0.5}\ {\rm ergs\ cm^{-3}\ s^{-1}} \\ &\approx 0.036E_{\rm S}(M_5^{\rm HC})^{-1.5}\,. \end{aligned} \tag{18}$$

The energy loss through neutrinos cannot be greater than the gravitational binding energy itself. Therefore, for $M_5^{\rm HC} \lesssim 0.1$, the neutrino loss will saturate the limit of the gravitational binding energy, and the above scaling with $M_5^{\rm HC}$ will break down. In fact, when $M_5^{\rm HC} \lesssim 0.1$, we do not expect our calculations to apply in the first place, because

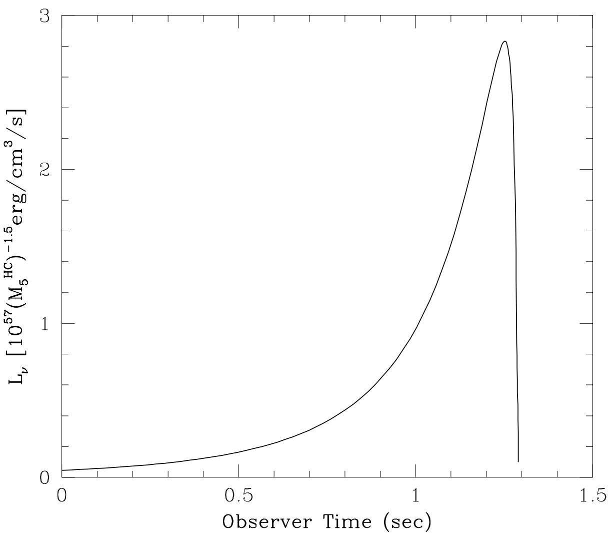

FIG. 2.—Time evolution of the neutrino luminosity according to eq. (17), for $M_5^{HC} = 1$. The neutrino emission stops when the radius of the core R enters the horizon.

neutrinos become trapped in the core instead of freely streaming out.

So far we have assumed that the radius of the core collapses at the speed of light at the black hole formation point. The neutrino energy loss and luminosity can be significantly larger than we have calculated if rapid rotation or strong magnetic fields slow down the collapse appreciably. In these cases, not only will the time available for neutrino release be longer, but the time delay factor ϵ_1 will be less damaging.

3. THE NEUTRINO SPECTRUM FROM THE COLLAPSE OF A SUPERMASSIVE STAR

The energy spectra associated with neutrino emission from the annihilation of e^+e^- plasma with a temperature T is best estimated using a Monte Carlo method: we pick an electron-positron pair from a thermal distribution at temperature T and randomly distribute the momentum of one neutrino in all directions in the center-of-mass frame. The energies and momenta of the two neutrinos produced are then fixed by momentum and energy conservation. We then convert the neutrino energies back into the rest frame and count each annihilation as $|M|^2$ events, where the amplitude of the annihilation matrix element is

$$|M|^2 = \text{constant} \times \{(a^2 + b^2)[(p_{e^-} \cdot q_\nu)(p_{e^+} \cdot q_{\bar\nu}) + (p_{e^-} \cdot q_{\bar\nu})(p_{e^+} \cdot q_\nu)] + (a^2 - b^2)m_e^2(q_\nu \cdot q_{\bar\nu})\} \quad (19)$$

(Dicus 1972).

In this equation the p's and q's are four-momenta of e^+, e^-, ν, and $\bar\nu$, and m_e is the electron rest mass. The coefficients are

$$a = 1 \pm 2 \sin\theta_w \,, \quad b = 0.5 \,, \quad (20)$$

where $\sin\theta_w \approx 0.23$, the plus (+) sign is for ν_e, and the minus (−) sign is for ν_μ and ν_τ.

After repeating the same process many times (several billion times in our case) and tallying the total number of events that correspond to various energy bins, we have an unnormalized neutrino energy spectrum resulting from e^+e^- annihilation in a steady state equilibrium plasma. All three neutrino species share a common normalization so that the calculation gives a relative flux between $\nu_e\bar\nu_e$ and $\nu_\mu\bar\nu_\mu$ (or $\nu_\tau\bar\nu_\tau$), which is around 4.7:1 as long as $T \gtrsim m_e \approx 0.5$ MeV. The simulation also yields the temperature dependence of the neutrino fluxes, which is proportional to T^8 if $T \gtrsim m_e$, consistent with theoretical expectations.

We *fit* the neutrino spectrum (normalized energy distribution function) to the form

$$f_\nu = \frac{1}{T_\nu^3 F_2(\eta_\nu)} \frac{E^2}{e^{(E/T_\nu)-\eta_\nu} + 1} \,, \quad (21)$$

where the relativistic Fermi integrals are

$$F_k(\eta_\nu) = \int_0^\infty \frac{x^k\,dx}{e^{x-\eta_\nu} + 1} \,. \quad (22)$$

We find that for $T \gtrsim 0.5$ MeV, $T_\nu \approx 1.6T$, and $\eta_\nu \approx 2$ for all neutrino species. The average neutrino energy is $\approx 5.5T$, higher than that of the ambient e^+e^- plasma. This is because (1) electrons and positrons with higher energies have larger cross sections for annihilation into neutrinos, and (2) the mass of the electron and positron add into the energy of the neutrinos.

Figure 3 shows the arbitrarily normalized neutrino energy spectrum calculated from our Monte Carlo method and the analytical fit, at $T = 1.5$ MeV. The analytical fit is remarkably good. Similar goodness of fit is also obtained for a variety of temperatures T, ranging from 0.5 MeV to 10 MeV, fully covering the typical temperatures inside a collapsing supermassive star.

The neutrino spectrum from the collapse of a supermassive star can be estimated from the single-temperature spectrum (eq. [21]) averaged over the entire core and over its time evolution. A precise account is not warranted at this stage. As an estimate, we simply take the e^+e^- temperature

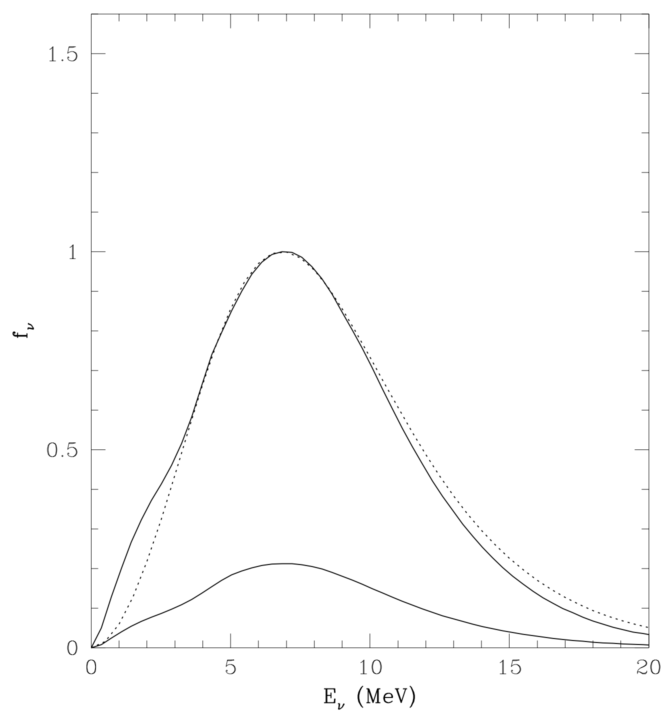

FIG. 3.—*Solid lines*: Spectra of $\nu_e\bar\nu_e$ (*upper*) and $\nu_\mu\bar\nu_\mu$ (or $\nu_\tau\bar\nu_\tau$; *lower*) emission due to e^+e^- annihilation during the collapse of a supermassive star with an assumed core temperature $T = 1.5$ MeV. The dotted line is the analytical fit to the $\nu_e\bar\nu_e$ spectrum. A common arbitrary normalization applies to all curves.

to be that at the peak neutrino emission point in both space and time. That is, we estimate it at a position $r \approx 0.14R$ (from Fig. 1) where neutrinos emitted at this position emerge from the core when $\beta \approx \frac{7}{6}$ (from Fig. 2). This turns out to be $T \sim 0.8(M_5^{\rm HC})^{-1/2}$ MeV. Therefore the neutrino spectrum from a supermassive star with a core mass of $M_5^{\rm HC}$ is, to a fair approximation,

$$f_\nu \approx \frac{1}{(0.8\ {\rm MeV}/\sqrt{M_5^{\rm HC}})^3 F_2(2)} \frac{E^2}{e^{(E\sqrt{M_5{}^{\rm HC}}/1.2\ {\rm MeV})^{-2}} + 1}, \quad (23)$$

with an average energy

$$\langle E_\nu \rangle \approx 4(M_5^{\rm HC})^{-1/2}\ {\rm MeV}. \quad (24)$$

The average energy can be a factor of 2 higher if the collapse is slowed down significantly by rotation/magnetic fields, in such a way that the travel time difference is much less important.

4. NEUTRINO BACKGROUND FROM SUPERMASSIVE STARS AND PROSPECTS FOR DETECTION

If supermassive stars were ever ubiquitous in the universe, they would have left a significant neutrino background. Assuming that a fraction F of all baryons once resided in supermassive stars, and a fraction f of the associated gravitational binding energy was released by neutrino emission, then the total background flux from this neutrino background is now

$$\phi_\nu \sim F f \rho_b c^3/\langle E_\nu \rangle, \quad (25)$$

where ρ_b is the baryon density today, and $\langle E_\nu \rangle$ is the average energy of the neutrinos from the collapse of supermassive stars. About 70% of the flux is $\nu_e \bar{\nu}_e$, and 15% of the flux is $\nu_\mu \bar{\nu}_\mu$ or $\nu_\tau \bar{\nu}_\tau$. Since, from equations (18) and (24), $f_{0.1} = f/0.1$ is usually of order 1 and $\langle E_\nu \rangle \sim 10$ MeV, we have

$$\phi_\nu \sim 10^5 F f_{0.1} \left(\frac{\Omega_b h^2}{0.025}\right)\left(\frac{10\ {\rm MeV}}{\langle E_\nu \rangle}\right) {\rm cm}^{-2}\ {\rm s}^{-1}, \quad (26)$$

where Ω_b is ρ_b divided by the critical density today, and h is the present-day Hubble parameter in units of 100 km s^{-1} Mpc^{-1}.

If F is 10%, a fraction that is certainly allowed by known constraints, then the flux of background neutrinos from supermassive stars can be 100 times higher than the neutrino background from supernovae (Totani et al. 1996; Hartmann & Woosley 1997; Malaney 1997). This is because metallicity considerations tightly constrain the fraction of baryons once in supernova progenitors to be $\lesssim 10^{-3}$, while the number and energy of neutrinos released per baryon may not differ much in the two kinds of collapse event (supernovae vs. supermassive stars). The fraction of higher energy neutrinos ($\gtrsim 10$ MeV) in the neutrino background from supermassive stars is, however, very likely to be much smaller than that of the supernova neutrino background. This is because neutrinos coming from supermassive stars suffer a redshift factor $(1 + z)$ if supermassive stars formed and collapsed at a redshift of $z \gtrsim 1$, making the detection of these neutrinos very difficult. For example, if $z \gtrsim 3$, the average energy of the neutrino background from supermassive stars will be only $\lesssim 1.4(M_5^{\rm HC})^{-0.5}$ MeV, far below the threshold of the currently running SuperK experiment (about 7 MeV). Further complicating the detection of supermassive star relic neutrinos is the fact that ν_e in the background will be hopelessly buried in the solar neutrino flux, which is $\sim 10^9$ cm^{-2} s^{-1} at ≈ 1 MeV and $\sim 10^6$ cm^{-2} s^{-1} at ≈ 10 MeV; and the $\bar{\nu}_e$ flux in the background under the optimal condition $F \sim 10\%$ will be comparable to or less than the terrestrial $\bar{\nu}_e$ background from nuclear power stations, which ranges from 10^5 to 10^7 cm^{-2} s^{-1} at the various sites of neutrino detectors (Lagage 1985). Clearly, an earth-bound detection of the neutrino background from supermassive stars will be extremely difficult, if not impossible.

As worked examples, we calculate the expected event rate from the supermassive star neutrino background in several new-generation neutrino detectors, including the currently-running SuperK. The fiducial masses, thresholds, and detection channels of these experiments are listed in Table 1. Figure 4 shows the expected event rates as a function of z, the redshift at which all supermassive stars existed. We

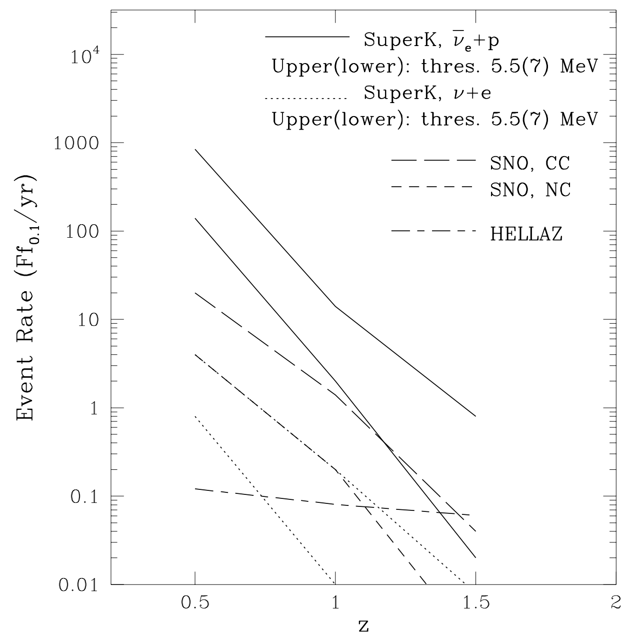

FIG. 4.—Event rates from the supermassive star neutrino background in several new-generation detectors, as a function of the redshift z of supermassive star collapse, for $M_5^{\rm HC} = 1$.

TABLE 1

NEW-GENERATION NEUTRINO DETECTORS FOR WHICH RATES ARE CALCULATED

Parameter	Super Kamiokande	SNO	HELLAZ
Detection channel......	$\bar{\nu}_e p \rightarrow n e^+$ $\nu e^- \rightarrow \nu e^-$	$\nu_e d \rightarrow p p e^-$ (CC) $\nu d \rightarrow \nu p n$ (NC)	$\nu e^- \rightarrow \nu e^-$
Threshold (MeV).......	7 (current) 5.5 (planned)	5	0.1
Fiducial mass...........	22.5 kton	1 kton	6 ton

adopt a neutrino spectrum of the form in equation (21), assuming $M_5^{\rm HC} = 1$, and we assume 100% detector efficiencies above the published thresholds. These assumptions are not entirely realistic, but they give good order-of-magnitude estimates. The event rates scale linearly with the abundance of supermassive stars (represented by F, the fraction of baryons in these stars) and $f_{0.1}$. From Figure 4 it can be seen that SuperK (Totsuka 1998) may potentially be able to preclude more than $\sim 10\%$ of baryons ever having been in the form of supermassive stars at a redshift of $z \ll 1$ (although such a conjecture may have already been ruled out by not seeing them directly!).

5. NEUTRINO BURST FROM COLLAPSE OF A SINGLE SUPERMASSIVE STAR

It is interesting to calculate the neutrino flux from the collapse of a single supermassive star and see what the requirement would be for detectors to observe such an event. If the collapse occurred at redshift z, its neutrino fluence now is

$$\phi_\nu t \sim \frac{fM^{\rm HC}c^2}{4\pi d_L^2 \langle E_\nu \rangle} \approx (4 \times 10^5 \ {\rm cm}^{-2}) f_{0.1} (M_5^{\rm HC})^{3/2} \times \left(\frac{10 \ {\rm MeV}}{\langle E_\nu \rangle}\right)\left(\frac{6000 \ {\rm Mpc}}{d_L}\right)^2 , \quad (27)$$

where d_L is the luminosity distance to the star. The average neutrino energy now would be $\langle E_\nu \rangle/(1+z) \sim 4(M_5^{\rm HC})^{-1/2}(1+z)^{-1}$ MeV.

The duration of the neutrino burst, t, is dilated to $M_5^{\rm c}(1+z)$ s, or longer if rotation and/or magnetic fields prolong the collapse. As long as $z \gtrsim 1$, then we can conclude that $d_L \sim 6000$ Mpc. This burst can be converted roughly into numbers of events in detectors by scaling from equation (26) and Figure 4. The number of events in the detectors are the yearly event rates in Figure 4 (with $F = 1$) multiplied by $10^{-7} f_{0.1} (M_5^{\rm HC})^{3/2}$. For example, a neutrino burst from a nonrotating, nonmagnetized, collapsing supermassive star with $M_5^{\rm c} = 1$ at $z = 1$ induces 10^{-6} events in SuperK. This obviously is impossible to detect. The ν_e flux in the burst will be completely swamped by the solar neutrino flux unless $z \ll 1$. The $\bar{\nu}_e$ flux in this example burst, on the other hand, is comparable to the terrestrial $\bar{\nu}_e$ background from nuclear reactors. The supermassive star $\bar{\nu}_e$ component can only stand out from the nuclear reactor neutrinos when $z \ll 1$, when their average energy will be higher than the 3 MeV peak energy of neutrinos from reactors. Therefore, it seems that the best chance to detect such a neutrino burst from a distant supermassive star is in space, in reactions induced by $\bar{\nu}_e$, and with extremely large detectors. As a simplistic example, to establish a burst signal requires a minimum of about 10 $\bar{\nu}_e p \to n e^+$ events to be detected within a duration of ~ 10 s. On Earth, this requires a 3×10^{10} ton SuperK-type detector for a supermassive star of $M_5^{\rm HC} = 1$ at $z = 1$. But in space, there may be a significantly lower $\bar{\nu}_e$ background, so that the mass of the detector needed will be substantially smaller. One possibility could be an AMANDA (Antarctic Muon and Neutrino Detector Array; Barwick et al. 1991) with a threshold of $\lesssim 5$ MeV built on an inactive icy asteroid or satellite of outer planets.

The frequency of neutrino bursts from supermassive stars (or the frequency of collapse of supermassive stars) could be nonnegligible. Assuming that they all form and collapse at a redshift z, the frequency of these collapse events as observed now is

$$\sim 4\pi r^2 a_z^3 \frac{dr}{dt_0} \frac{\rho_b (1+z)^3 F}{M} , \quad (28)$$

where r is the comoving FRW coordinate of these supermassive stars (with Earth at the origin), a_z is the scale factor of the universe at a redshift z (with $a_0 = 1$), t_0 is the age of the universe, $\rho_b \approx 2 \times 10^{-29}$ g cm^{-3} $\Omega_b h^2 \approx 5 \times 10^{-31}$ g cm^{-3} (Tytler & Burles 1997) is the baryon density of the universe today, and M is the mass of a typical supermassive star. Since $dr/dt_0 \approx c$, the speed of light, and r is of order 6000 h^{-1} Mpc as long as $z > 1$, this frequency is

$$0.3 F M_5^{-1} \ {\rm s}^{-1} \sim 3 \times 10^4 F M_5^{-1} \ {\rm day}^{-1} . \quad (29)$$

Therefore, even with $F \sim 0.004\%$ (i.e., 0.004% of all baryons were incorporated at one time into $10^5 M_\odot$ supermassive stars), these neutrino bursts would be occurring on average about once a day, comparable to the occurrence rate of γ-ray bursts.

6. SUMMARY

In this paper we have calculated the neutrino luminosity and spectrum from the $e^+e^- \to \nu\bar{\nu}$ process during the collapse of a supermassive star. We have estimated that for a typical supermassive star with a homologous core mass of 10^5 $M_\odot$, a few percent or higher of the total gravitational energy can be carried away by neutrinos, with an average energy $\sim$4–8 MeV, with both the percentage efficiency and the average energy depending on the timescale of the collapse. We have further calculated the flux and energy spectrum of the neutrino background from a population of supermassive stars. This has been done as a function of the redshift of these stars, their abundance, and their efficiency in converting gravitational binding energy into neutrino energy. We found that the resulting neutrino background could potentially have a higher flux than the supernova neutrino background. However, the average energy of this background flux would likely be lower, because supermassive stars more likely formed at a high redshift, if they ever formed at all. The expected event rates for this background were calculated for several new-generation neutrino detectors, including SuperK. We showed that SuperK may potentially be able to rule out the possibility that more than $\sim 10\%$ of baryons could have been incorporated in supermassive stars at a redshift $z \ll 1$. Finally, we calculated the flux and energy of the neutrino burst resulting from the collapse of a single supermassive star and assessed its detectability. These events are extraordinarily difficult to detect. The frequency of such burst events—or, equivalently, the collapse event rate of supermassive stars—is also shown to be possibly significant, easily matching or exceeding the frequency of occurrence of γ-ray bursts.

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REFERENCES

Barwick, S. W., et al. 1991, in Proc. 22nd Int. Cosmic Ray Conf., Vol. 4 (Dublin: Dublin Inst. Adv. Stud.), 658
Begelman, M. C., & Rees, M. J. 1978, MNRAS, 185, 847
Bond, J. R., Arnett, W. D., & Carr, B. J. 1984, ApJ, 280, 825
Dicus, D. A. 1972, Phys. Rev. D, 6, 941
Fuller, G. M., & Shi, X. 1997, ApJ, 487, L25
Fuller, G. M., Woosley, S. E., & Weaver, T. A. 1986, ApJ, 307, 675 (FWW)
Goldreich, P., & Weber, S. V. 1980, ApJ, 238, 991
Hartmann, D. H., & Woosley, S. E. 1997, Astropart. Phys., 7, 137
Hoyle, F., & Fowler, W. A. 1963, MNRAS, 125, 169
Itoh, N., Adachi, T., Nakagawa, M., Kohyama, Y., & Munakawa, H. 1989, ApJ, 339, 354
Lagage, P. O. 1985, Nature, 316, 420
Malaney, R. A. 1997, Astropart. Phys., 7, 125
McLaughlin, G. C., & Fuller, G. M. 1996, ApJ, 456, 71
Peebles, P. J. E., & Dicke, R. H. 1968, ApJ, 154, 891
Schinder, P. J., et al. 1987, ApJ, 313, 531
Tegmark, M., et al. 1997, ApJ, 474, 1
Totani, T., Sato, K., & Yoshii, Y. 1996, ApJ, 460, 303
Totsuka, Y. 1998, in Proc. 18th Texas Symp. on Relativistic Astrophysics, ed. A. Olinto, J. Frieman, & D. Schramm (Singapore: World Scientific), in press
Tytler, D., & Burles, S. 1997, in Origin of Matter and Evolution of Galaxies, ed. T. Kajino, Y. Yoshii, & S. Kubono (Singapore: World Scientific), 37
van der Marel, R. P., de Zeeuw, P. T., Rix, H., & Quinlan, G. D. 1997, Nature, 385, 610
Wallace, R. K., & Woosley, S. E. 1981, ApJS, 45, 389
Weinberg, S. 1972, Gravitation and Cosmology (New York: Wiley)
Woosley, S. E. 1977, Nature, 269, 42