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## SUPERMASSIVE OBJECTS AS GAMMA-RAY BURSTERS

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### ABSTRACT

We propose that the gravitational collapse of supermassive objects ( $M \geq 10^4 M_\odot$ ), either as relativistic star clusters or as single supermassive stars (which may result from stellar mergers in dense star clusters), could be a cosmological source of  $\gamma$ -ray bursts. These events could provide the seeds of the supermassive black holes observed at the center of many galaxies. Collapsing supermassive objects will release a fraction of their huge gravitational binding energy as thermal neutrino pairs. We show that the accompanying neutrino/antineutrino annihilation-induced heating could drive electron/positron “fireball” formation, relativistic expansion, and associated  $\gamma$ -ray emission. The major advantage of this model is its energetics: supermassive object collapses are far more energetic than solar mass-scale compact object mergers; therefore, the conversion of gravitational energy to fireball kinetic energy in the supermassive object scenario need not be highly efficient, nor is it necessary to invoke directional beaming. The major weakness of this model is difficulty in avoiding a baryon-loading problem for one dimensional collapse scenarios.

*Subject headings:* cosmology: observations — cosmology: theory — gamma rays: bursts

### 1. INTRODUCTION

In this Letter we propose that the collapse of supermassive objects and the associated neutrino/antineutrino annihilation could give rise to high-redshift (cosmological)  $\gamma$ -ray bursts (GRBs). This model could alleviate vexing problems associated with the energetics of conventional stellar remnant-based scenarios. We define a supermassive object to be a star or star cluster that suffers the general relativistic Feynman-Chandrasekhar instability during its evolution. This corresponds to objects with initial masses  $M \geq 10^4 M_\odot$ , i.e., those which may leave black hole remnants with masses  $M \geq 10^3 M_\odot$ .

Detections of absorption and emission features at a redshift  $z = 0.835$  in the spectral observation of the afterglow of  $\gamma$ -ray burst GRB 970508 (Metzger et al. 1997a, 1997b) and at redshift  $z = 3.42$  in the host galaxy of GRB 971214 (Kulkarni et al. 1998) have established that at least some of the GRB sources lie at cosmological distances. Observations show that the total energy in gamma rays associated with a GRB at cosmological distances is  $\sim 10^{52}$  to  $\sim 10^{53}$  ergs when a  $4\pi$  solid angle coverage is assumed (Fenimore et al. 1993; Wijers et al. 1998; Kulkarni et al. 1998). Catastrophic collapse events, such as neutron-star/neutron-star mergers (Paczynski 1986; Goodman 1986; Eichler et al. 1989), neutron-star/black-hole mergers (Mochkovitch et al. 1993), failed supernovae (Woosley 1993), “hypernovae” (Paczynski 1998), and collapse of Chandrasekhar-mass white dwarfs (Usov 1992), have been touted as natural candidates for cosmological GRB sources. Fireballs created in these collapse events could accelerate material to the ultrarelativistic regime, with Lorentz factors  $\Gamma = E_e/m_e c^2 \geq 10^2$  (Paczynski 1986; Goodman 1986; Rees & Mészáros 1992; Mészáros & Rees 1992). The kinetic energy in these fireballs could then be converted to  $\gamma$ -rays possibly via the cyclotron radiation and/or the inverse Compton processes associated with ultrarelativistic electrons. In these models, the energy loss of the shock(s) propelled by the fireball would produce the afterglow associated with a GRB event (Waxman 1997).

There are, however, problems for these stellar remnant-based models if the GRBs originate from high-redshift events. The total gravitational binding energy released when a  $\sim 1 M_\odot$  configuration collapses to a black hole (or into a preexisting larger

black hole) is only  $\sim 10^{54}$  ergs. Calculations have shown that it is very difficult to power a GRB of energy  $\sim 10^{52}$  ergs (Wijers et al. 1998) or an afterglow with a similar energy (Waxman 1997; Dar 1997) with such a collapse scenario, unless the  $\gamma$ -ray emission and the blast wave causing the afterglow are highly collimated (improbably highly collimated in the case of very high-redshift events).

This energetics problem can be avoided in the supermassive object collapse model suggested here. Collapse of such large mass scale objects could result in prodigious gravitational binding energy release. Some of this gravitational energy is radiated as thermal neutrino/antineutrino pairs (Fuller, Woosley, & Weaver 1986, hereafter FWW; Fuller & Shi 1997) whose annihilations into electron/positron pairs could create a fireball above the core that generates  $\gamma$ -rays. There is no direct evidence for supermassive stars ever having been extant in the universe. However, it has been argued that their formation could be an inevitable result of the collapse of  $\sim 10^5 M_\odot$ – $10^6 M_\odot$  primordial clouds (the baryon Jean’s mass at early epochs, see Peebles & Dicke 1968 and Tegmark et al. 1997) at high redshifts in which cooling was not as efficient as in clouds contaminated with metals, or more likely, as a result of stellar mergers associated with  $\geq 10^7$ – $10^8 M_\odot$  relativistic star cluster collapse (Hoyle & Fowler 1963; Begelman & Rees 1978; Bond, Arnett, & Carr 1984; FWW; McLaughlin & Fuller 1996). The flow chart for supermassive black hole production suggested by Begelman & Rees (1978) includes several pathways whereby supermassive stars are formed in the central region of the collapsing cluster. Further, supermassive black holes apparently are ubiquitous in the universe. They are invoked as the central engines of active galactic nuclei (AGNs) and quasars and are inferred to be in the centers of nearby galaxies (van der Marel et al. 1997).

We note that Prilutski & Usov (1975) have previously tied GRBs to magneto-energy transfer during collapses of supermassive rotators ( $\sim 10^6 M_\odot$ ) postulated to power AGNs and quasars. Here we propose a different energy transfer mechanism (neutrinos) based on objects not necessarily tied to AGNs or quasars, but that could possibly be related to the birth of the supermassive black holes that power them.

## 2. FIREBALLS FROM SUPERMASSIVE OBJECT COLLAPSE

Supermassive stars will suffer the general relativistic (Feynman-Chandrasekhar) instability, either at or before the onset of hydrogen burning (cf. FWW) in the case of quasi-statically contracting objects, or immediately upon formation as in the case where stellar mergers produce them. As such a star collapses, the entropy per baryon is slightly increased by nuclear burning, but then is reduced by neutrino pair emission. Though initially the whole star can collapse homologously, as the entropy is reduced only an inner “homologous core” can continue to collapse homologously (FWW). It is this homologous core that will plunge through an event horizon as a unit to make a black hole. The mass of the homologous core,  $M_5^{\text{HC}} \equiv M^{\text{HC}}/10^5 M_\odot$ , can be much smaller (possibly by 1 order of magnitude or more) than the mass of the initial hydrostatic supermassive star,  $M_5^{\text{init}} \equiv M^{\text{init}}/10^5 M_\odot$ .

The collapse to a black hole of a supermassive star with a homologous core mass  $M^{\text{HC}}$  will have a characteristic (prompt) Newtonian gravitational binding energy release of  $\sim E_s \approx 10^{59} M_5^{\text{HC}}$  ergs. During the collapse, neutrino emission will ensue from  $e^\pm$ -annihilation in the core. The emissivity of this process scales as the core temperature to the *ninth* power (Dicus 1972). As a result, most of the gravitational binding energy removed by neutrinos will be emitted very near the point where the core becomes a black hole, and on a timescale characterized by the free-fall time (or light crossing time) of the homologous core near the black hole formation point. We employ a characteristic free-fall collapse timescale of  $t_s \approx M_5^{\text{HC}}$  s and a characteristic radius (the Schwarzschild radius) of  $r_s \approx 3 \times 10^{10} M_5^{\text{HC}}$  cm. For a core mass  $\geq 10^4 M_\odot$  the neutrinos will not be trapped in the core and will freely stream out. For a smaller core mass, the neutrino diffusion timescale will be long compared to the free-fall timescale, and so neutrinos will be trapped in the core. Neutrino emission in this latter case will be from a “neutrino sphere” at the edge of the homologous core.

In general it is difficult to estimate the range of initial stellar masses that will give rise to a given range of homologous core masses, though there is a clear hierarchy at each evolutionary stage. We therefore guess that the initial star cluster masses will be in the range  $10^5$ – $10^9 M_\odot$ , while the subsequently produced supermassive stars will have masses  $M_5^{\text{init}} \approx 0.1$  to  $\sim 1000$ , while the corresponding homologous core masses will lie in the range  $M_5^{\text{HC}} \approx 10^{-2}$  to  $\sim 10$ . Figure 1 shows a flow chart for the collapse of supermassive objects.

The neutrino luminosity can be crudely estimated from the product of the neutrino energy emissivity (Schinder et al. 1987; Itoh et al. 1989) near the black hole formation point and the volume inside the Schwarzschild radius, i.e.,  $4 \times 10^{15} (T_9^{\text{Schw}})^9 (4\pi r_s^3/3)$  ergs  $s^{-1}$ . Here  $T_9^{\text{Schw}}$  is the characteristic *average* core temperature near the black hole formation point in units of  $10^9$  K. For a spherical nonrotating supermassive star we can show that

$$T_9^{\text{Schw}} \approx 12 \alpha_{\text{Schw}}^{1/3} \left( \frac{11/2}{g_s} \right)^{1/3} \left( \frac{M_5^{\text{init}}}{M_5^{\text{HC}}} \right)^{1/6} (M_5^{\text{HC}})^{-1/2}, \quad (1)$$

where  $\alpha_{\text{Schw}}$  is the ratio of the final entropy per baryon to the value of this quantity in the initial precollapse hydrostatic configuration, and  $g_s \approx g_b + 7/8 g_f \approx 11/2$  is the statistical weight of relativistic particles in the core. Since for spherical nonrotating supermassive stars  $M_5^{\text{init}}/M_5^{\text{HC}} \approx (5.5/2)^{1/2} \alpha_{\text{Schw}}^{-2}$  (FWW), we can conclude that  $T_9^{\text{Schw}} \approx 13 (M_5^{\text{HC}})^{-1/2}$ . The characteristic

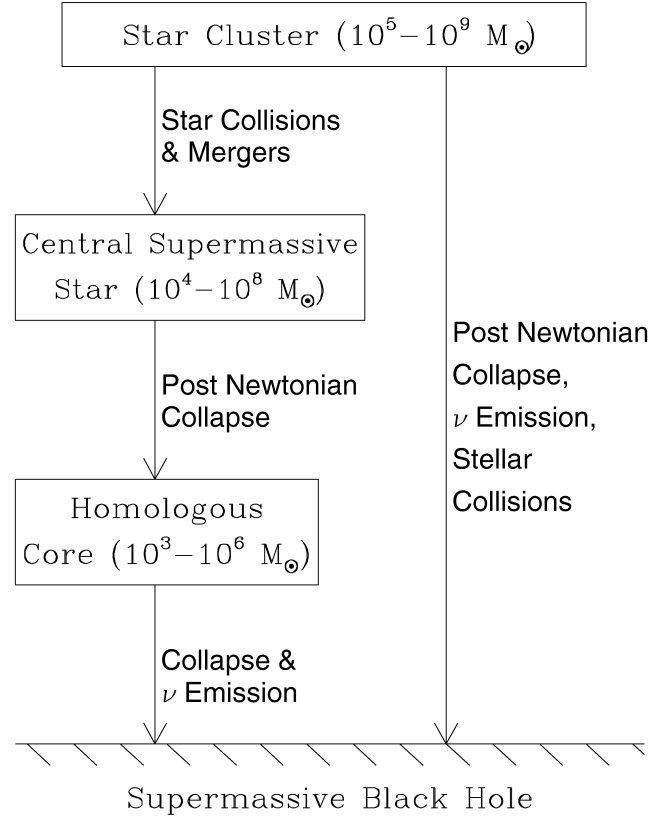


FIG. 1.—Flow chart for the collapse of supermassive objects

neutrino luminosity is then

$$\begin{aligned} L_{\nu\bar{\nu}} &\sim 4 \times 10^{15} (T_9^{\text{Schw}})^9 (4\pi r_s^3/3) \text{ ergs } s^{-1} \\ &\approx 5 \times 10^{57} (M_5^{\text{HC}})^{-3/2} \text{ ergs } s^{-1}. \end{aligned} \quad (2)$$

Since 70% of the neutrino emission is in the  $\nu_e \bar{\nu}_e$  channel, the characteristic luminosity of  $\nu_e$  or  $\bar{\nu}_e$  is  $L_{\nu_e} = L_{\bar{\nu}_e} \approx 0.35 L_{\nu\bar{\nu}}$ . (This estimate of  $L_{\nu\bar{\nu}}$  is a factor of  $\sim 10$  above an appropriately scaled version of the Woosley, Wilson, & Mayle 1986 result for a  $M_5^{\text{init}} = 5$  configuration; part of the difference is attributable to the employment of different neutrino emissivities, and the remainder may result from different core temperatures.)

The copious  $\nu\bar{\nu}$  emission during the collapse can create a fireball above the homologous core by  $\nu\bar{\nu} \rightarrow e^+e^-$ . Clearly, the neutrino luminosities will suffer gravitational redshift, which will degrade the total energy deposition above the star, though this will be compensated by increased  $\nu\bar{\nu}$ -annihilation from gravitational bending of null trajectories (Cardall & Fuller 1997). A detailed calculation of these two effects is beyond the scope of this Letter, but we do not expect the combination of them to change our order-of-magnitude estimates significantly. The energy deposition rate per unit volume from the  $\nu\bar{\nu}$  annihilation at a radius  $r$  above a spherical shell of thermal neutrino emission with a radius  $R_\nu$ , is then (Goodman, Dar, & Nussinov 1987; Cooperstein, van den Horn, & Baron 1987)

$$\dot{Q}_{\nu\bar{\nu}}(r) = \frac{KG_F^2 \Phi(x) \hbar^2 c}{12\pi^2 R_\nu^4} L_\nu L_{\bar{\nu}} \left( \frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle} + \frac{\langle E_{\bar{\nu}}^2 \rangle}{\langle E_{\bar{\nu}} \rangle} \right). \quad (3)$$

Here  $G_F$  is the Fermi constant,  $L$  is the luminosity of the neutrinos/antineutrinos, and the brackets denote averages of neutrino energy or squared energy over the appropriate neutrino or antineutrino energy spectra (see Shi & Fuller 1998). The phase space and spin factors are  $K \approx 0.124(0.027)$  for  $\nu = \nu_e(\nu_\mu, \nu_\tau)$ , and the radial dependence of the energy deposition rate is  $\Phi(x) = (1-x)^4(x^2 + 4x + 5)$ , with  $x = [1 - (R_\nu/r)^2]^{1/2}$ .

The characteristic neutrino luminosity  $L_{\nu\bar{\nu}}$  in equation (2) could be an underestimate of the true neutrino luminosity. A detailed numerical calculation (without considering the uncertain gravitational redshift, however) shows that the true average neutrino luminosity can be much higher if there is rapid rotation and/or magnetic fields holding up the collapse (Shi & Fuller 1998). The neutrino energy loss rate scales steeply as  $T_\nu^9$ , and the temperature distribution in the homologously collapsing core (an index  $n = 3$  polytrope) follows the Lane-Emden function and so peaks at the center. Compensating this feature will be the  $R_\nu^4$  dependence of the above  $\nu\bar{\nu}$  energy deposition rate  $\dot{Q}_{\nu\bar{\nu}}$ . Therefore, we will approximate the entire neutrino emissivity of the core as arising from the edge of the core ( $R_\nu \sim r_s$ ), and then take  $L_{\nu\bar{\nu}}$  as the characteristic neutrino luminosity from equation (2). (Note that this equation is appropriate in the case where  $M_5^{\text{HC}} \lesssim 0.1$  and neutrinos diffuse from the core. In this case, the central temperature is irrelevant, though we may get luminosities comparable to the free-streaming case because the core will have lower mass and, hence, a generally higher temperature scale.)

The expected near-thermal spectrum of the neutrino emission implies  $\langle E_\nu^2 \rangle / \langle E_\nu \rangle = \langle E_{\bar{\nu}}^2 \rangle / \langle E_{\bar{\nu}} \rangle \approx 6(M_5^{\text{HC}})^{-1/2} \text{ MeV}$  (Shi & Fuller 1998). Therefore, the neutrino energy deposition rate per unit volume will be roughly

$$\dot{Q}_{\nu\bar{\nu}}(r) \sim 4 \times 10^{22} (M_5^{\text{HC}})^{-7.5} (r_s/r)^8 \text{ ergs cm}^{-3} \text{ s}^{-1}. \quad (4)$$

The total energy deposited into the fireball above a radius  $r$  is

$$E_{\text{f.b.}}(r) = t_s \int_r^\infty 4\pi r^2 \dot{Q}_{\nu\bar{\nu}}(r) dr \\ \sim 2.5 \times 10^{54} (M_5^{\text{HC}})^{-3.5} (r_s/r)^5 \text{ ergs}, \quad (5)$$

which is tremendous. The fireball will undoubtedly lose some of this energy to thermal neutrino emission. But, once the  $e^\pm$  pair density is high enough for this, neutrino/electron scattering should deposit even more energy. If  $M_5^{\text{HC}} = 0.5$ , the energy deposited in the fireball will be  $\sim 10^{53}$  ergs at a radius  $r \sim 3r_s \sim 10^{11}$  cm. This is the total observed energy in a GRB assuming a  $4\pi$  solid angle and a redshift  $z \sim 3$ .

A successful model of GRBs must avoid excessive baryon loading so that a Lorentz factor of  $\Gamma \gtrsim 10^2$  can be achieved for the baryons accelerated by the fireball. This suggests that the region at several Schwarzschild radii from the supermassive star core should have extremely low baryon density. This may be satisfied if the *whole* star collapses homologously into a black hole, and/or substantial rotation causes the star to collapse in a flattened geometry with very little material in the polar directions (an extreme case of this geometry was discussed in Bardeen & Wagoner 1969). The homologous collapse of the entire star could be engineered only if the star has substantial centrifugal support from rotation and/or if there is significant magnetic pressure (but not so much that an explosion results).

Therefore, rotation could be a crucial factor in this picture. Rotation will also result in a longer collapse timescale, and mildly beamed  $\gamma$ -ray emission. A high angular momentum collapse may therefore be challenged in generating GRBs with durations  $\lesssim 1$  s.

Another means to avoid excessive baryon loading may be possible in the collapse of a dense star cluster. In this case the whole star cluster can collapse on the general relativistic instability (Shapiro & Teukolsky 1985) and collisions of  $M_* \sim M_\odot$  stars could provide the neutrino “engine” that powers fireballs. During the collapse, the central stars will have relativistic speeds and the typical entropy per baryon produced in zero impact parameter collisions of these will be  $S \sim 10^4 \Gamma^{1/2} (g_*/5.5)^{1/4} (M_\odot/M_*)^{1/4} (V_*/V_\odot)^{1/4}$  with  $T_9 \sim 1$ , conditions commensurate with those required for hydrostatic supermassive stars [ $S \approx 10^4 (M^{\text{init}}/10^8 M_\odot)^{1/2}$ ]. (Here  $\Gamma \sim 1$  is an appropriate Lorentz factor, and  $V_*/V_\odot$  is the ratio of the stellar collision interaction volume to the solar volume.) In fact, most collisions will not be “head-ons” but rather will involve the tenuous outer layers of the stars. The lower densities involved will translate into larger entropies [effectively,  $(V_*/V_\odot)^{1/4}$  could be considerably larger], possibly large enough ( $S \sim 10^7$ ) to provide a pair fireball directly. In the collapse, space between moving stars may provide baryon-free “lanes,” and the stellar collisions themselves may cause the neutrino emission to be “spiky” (the overall emission profile, however, should nevertheless follow the free-fall collapse profile indicated above for supermassive stars). Both processes are stochastic, possibly contributing to the “spiky” time structure of the GRBs. This direct collapse of relativistic star clusters and the collapse of supermassive stars may well represent two extremes on a continuum of supermassive object collapse.

### 3. EVENT RATE AND PEAK FLUX DISTRIBUTION

The rate of supermassive object collapses should be able to match the observed rate of GRB events (several per day) if a substantial fraction of the burst events are to come from this source. Assuming that supermassive objects all form and collapse at a redshift  $z$ , the rate of these collapses as observed at the present epoch is

$$4\pi r^2 a_z^3 \frac{dr}{dt_0} \frac{\rho_b F (1+z)^3}{M^{\text{init}}}, \quad (6)$$

where  $r$  is the Friedman-Robertson-Walker comoving coordinate distance of the objects,  $a_z$  is the scale factor of the universe at the epoch corresponding to a redshift  $z$  (with  $a_0 = 1$ ),  $t_0$  is the age of the universe,  $\rho_b \approx 2 \times 10^{-29} \Omega_b h^2 \text{ g cm}^{-3} \approx 5 \times 10^{-31} \text{ g cm}^{-3}$  (Tytler & Burles 1997) is the baryon density of the universe today,  $h$  is the Hubble parameter in  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , and  $F$  is the fraction of baryons that were incorporated in supermassive objects. For  $z \sim 3$  we will have  $r \sim 3000 h^{-1} \text{ Mpc}$ . The collapse rate is therefore

$$0.15 F (M_5^{\text{init}})^{-1} \text{ s}^{-1} \sim 10^4 F (M_5^{\text{init}})^{-1} \text{ day}^{-1}, \quad (7)$$

with  $F \sim 0.1\%$ , i.e., with 0.1% of all baryons having been incorporated into supermassive objects of  $M_5^{\text{init}} \sim 10$ , we should observe (assuming a 100% detection efficiency) one collapse per day if they emitted  $\gamma$ -rays into a  $4\pi$  solid angle. This would constitute a substantial fraction of the observed rate of GRB events. The baryon fraction  $F = 0.1\%$  in  $\sim 10^6 M_\odot$  black holes

implies a (cumulative) density of  $7 h^2$  such supermassive black holes formed in  $1 \text{ Mpc}^3$ . This GRB rate is about 2 orders of magnitude lower than  $24 \text{ Gpc}^{-3} \text{ yr}^{-1}$ , the rate required if GRBs originate from source populations that do not evolve over time (Fenimore & Bloom 1995). This shortfall in rate results because we have assumed that all GRBs are high-redshift collapse events and are therefore seen from a larger volume. In addition, the rate of supermassive object collapses required in our GRB model does not depend on the mass scale of the collapsing objects, although the fraction  $F$  scales linearly with  $M_5^{\text{init}}$ . Observations show that almost all galaxies that have been examined appropriately seem to have supermassive black holes in their centers (van den Marel et al. 1997). It is therefore intriguing to estimate the rate of supermassive object collapses required by our GRB model on a per galaxy basis. If such supermassive object collapses occurred only in normal  $\sim L_*$  galaxies, the rate needed is about  $350 h^{-1}$  per  $L_*$  galaxy. However, this number of events per galaxy is much lower, perhaps  $\lesssim 10 h^{-1}$  per galaxy (based on, for example, the galaxy number densities of Zucca et al. 1997), if dwarf galaxies harbor supermassive objects as well. Therefore, it may be conceivable that these supermassive object collapse events are tied to the supermassive black holes at the centers of galaxies, if such supermassive black holes occur in every galaxy-scale object. Such an association of supermassive objects and galaxy-scale objects may also be born out by considering Lyman limit systems and damped Ly $\alpha$  systems, which are associated with galactic halos and disks at high redshifts. Using a column density  $N_{\text{HI}}$  distribution per unit column density per unit absorption distance of  $10^{13.9} N_{\text{HI}}^{-1.74}$  (Storrie-Lombardi, Irwin, & McMahon 1996), we find that the rate of supermassive object collapse matches that of GRBs if every Ly $\alpha$  system with  $N_{\text{HI}} \gtrsim 10^{18} \text{ cm}^{-2}$  harbors a supermassive object.

If all GRBs are from  $z \gtrsim 1$ , then the  $\gamma$ -ray burst peak flux distribution ( $\log N$ – $\log P$ ) will be very different from models with a homogeneously distributed population of GRBs. The observed  $\log N$ – $\log P$  distribution is a power law with index  $-1.5$ , which has a break at the faint end (Fenimore et al. 1993). This would be consistent with homogeneously distributed cosmological sources with a cutoff at high redshifts, unless the

peak flux of GRBs,  $P$ , cannot be regarded as a standard candle. But since the  $\log N$ – $\log P$  distribution is a convolution of the peak flux and spatial distribution, there is no guarantee that the observed power law requires a homogeneous distribution of sources. For our model, in which supermassive object collapses most likely occur at cosmological distances with  $z \gtrsim 1$ , we can always invoke variances in the peak flux of GRBs, and/or an evolution of supermassive object comoving number densities, or invoke another population of GRBs, to fit the observed  $\gamma$ -ray burst peak flux distribution. It is worth noting that even in existing stellar remnant-based models, the sources tend to be more abundant at  $z \gtrsim 1$ , because the star formation rate was higher then (Totani 1997).

#### 4. CONCLUSION

The formation of the supermassive black holes inferred in AGNs, quasars and many galaxies may well involve the collapse of relativistic star clusters that form intermediate phase supermassive stars. We point out here that collapses of these supermassive objects will be accompanied by prodigious thermal neutrino emission, which could transport a fraction of the gravitational binding energy of these objects to a region(s) in which the baryon loading is low, thus creating “clean” fireballs that generate  $\gamma$ -ray bursts. The major advantage of this model is a huge energy release, and just such an energy scale is required by recent observations of high-redshift bursts. We have shown that the collapse timescale and expected collapse event rates are consistent with  $\gamma$ -ray burst parameters. The principal weakness of our model is the baryon-loading problem. We have outlined possible ways to circumvent this problem by appealing to high angular momentum and flattened collapses and by appealing to the stochastic nature of stellar collision-induced supermassive star/black hole buildup in the collapse of relativistic star clusters.

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