Are Gamma-Ray Bursts Signals of Supermassive Black Hole Formation?

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Abstract.
The formation of supermassive black holes through the gravitational collapse of supermassive objects ($\mathrm{M} \gtrsim 5 \times 10^4\,\mathrm{M}_\odot$) has been proposed as a source of cosmological γ-ray bursts. The major advantage of this model is that such collapses are far more energetic than stellar-remnant mergers. The major drawback of this idea is the severe baryon loading problem in one-dimensional models. We can show that the observed $\log N - \log P$ (number vs. peak flux) distribution for gamma-ray bursts in the BATSE database is not inconsistent with an identification of supermassive object collapse as the origin of the gamma-ray bursts. This conclusion is valid for a range of plausible cosmological and γ-ray burst spectral parameters.

1. Introduction

We investigate aspects of a recent model for the internal engine powering γ-ray bursts (GRBs). This model produces a GRB fireball through neutrino emission and annihilation during the collapse of a supermassive object into a black hole (Fuller & Shi, 1998). This supermassive object may either be a relativistic cluster of stars or a single supermassive star. The collapse of a supermassive object provides an exceedingly large amount of energy to power the burst, much higher than the amount of energy available in stellar remnant models. In addition, the rate of collapse of these objects–when associated with galaxy-type structures–is similar to the GRB rate.

The recent observations of afterglows and galaxies associated with GRBs have secured that at least some have a cosmological origin and therefore must be extremely energetic events. The inferred redshifts of GRB 970508 and GRB 971214 suggest isotropic emission energies of $\sim 10^{52}$ and 3×10^{53} ergs (Metzger et al. 1997a, 1997b; Kulkarni et al. 1998). The energy in γ-rays alone for GRB 971214 is equivalent to 16% of the rest mass of the sun. Producing this amount of energy in γ-rays is difficult for stellar remnant collapse models, where the total amount of gravitational binding energy released in a $\sim 1\,M_\odot$ configuration is $\sim 10^{54}$ ergs (Wijers et al. 1998). However, *if* a stellar-remnant collapse manages to concentrate energy deposition into $\sim 1\%$ of the sky, then it *may* produce a burst with the observed energies.

Supermassive black holes are abundant in the universe. They are inferred to power active galactic nuclei (AGNs) and quasars; every galaxy examined so far seems to possess a supermassive black hole in its center (van der Marel et al. 1997). These black holes could have had supermassive objects as progenitors (Begelman & Rees 1978). Two venues of supermassive black hole formation are considered: in one, a dense cluster of $1\,M_\odot$ stars is disrupted by collisions and coalesces into a central supermassive star; in the second venue, the cluster as a whole undergoes a post newtonian collapse into a supermassive object. A supermassive star may also be formed directly through the collapse of a $\sim 10^5\,M_\odot - 10^6\,M_\odot$ primordial gas cloud when cooling in these is not efficient (Peebles & Dicke 1968 and Tegmark et al. 1997).

We will discuss the formation of a GRB fireball in both collapse scenarios. We will also address how the highly variable time structure of GRBs can occur in supermassive object collapse, and how the fireball can avoid "baryon-loading", which can incapacitate the formation of a relativistic fireball. It should be noted that Prilutski & Usov (1975) previously described the emission of a GRB from magneto-energy transfer during collapse of supermassive rotators ($\sim 10^6\,M_\odot$) believed to power AGNs and quasars. The neutrino energy transfer process we discuss is not necessarily tied to AGNs or quasars, but to the formation of the black holes powering them.

2. Fireballs from Supermassive Black Hole Formation

2.1. Supermassive Star Collapse

In the first venue of supermassive black hole formation, a supermassive star undergoes a general relativistic (Feynman-Chandrasekhar) instability. A core of mass $M_5^{\rm HC} \equiv M^{\rm HC}/10^5\,M_\odot$ collapses homologously and drops through the event horizon, releasing a gravitational binding energy of $\sim E_{\rm s} \approx 10^{59} M_5^{\rm HC}$ erg. The mass of the homologous core can be an order of magnitude (or more) less than the mass of the initial hydrostatic supermassive star, $M_5^{\rm init} \equiv M^{\rm init}/10^5\,M_\odot$.

During collapse, neutrinos are thermally emitted due to $e^\pm$ annihilation in the core. The luminosity of the neutrinos goes as the ninth power of the core temperature (Dicus 1972). This luminosity can be approximated from the product of neutrino emissivity (Schinder et al. 1987; Itoh et al. 1989) near the black hole formation point and the volume inside the Schwarzschild radius, $4\times 10^{15}\,(T_9^{\rm Schw})^9\,(4\pi r_{\rm s}^3/3)$ erg/sec, where $T_9^{\rm Schw}$ is the characteristic average core temperature in units of 10^9 K at the black hole formation epoch. In a spherical nonrotating supermassive star this is

$$T_9^{\rm Schw} \approx 12\alpha_{\rm Schw}^{1/3}\left(\frac{11/2}{g_{\rm s}}\right)^{1/3}\left(\frac{M_5^{\rm init}}{M_5^{\rm HC}}\right)^{1/6}\left(M_5^{\rm HC}\right)^{-1/2}. \quad (1)$$

Here $\alpha_{\rm Schw}$ is the ratio of the final entropy per baryon to the value of this quantity in the initial pre-collapse hydrostatic star, and $g_{\rm s} \approx g_b + 7/8 g_f \approx 11/2$ is the statistical weight of relativistic particles in the core. The characteristic free-fall timescale is labelled $t_{\rm s} \approx M_5^{\rm HC}$ sec, and the characteristic radius (the Schwarzschild radius) is $r_{\rm s} \approx 3\times 10^{10} M_5^{\rm HC}$ cm. It has been shown that the ratio of the homologous core mass to the initial mass is $M_5^{\rm HC}/M_5^{\rm init} \approx \sqrt{2/5.5}\,\alpha_{\rm Schw}^2$ (Fuller, Woosley & Weaver 1986), so that $T_9^{\rm Schw} \approx 13 (M_5^{\rm HC})^{-1/2}$. The neutrino luminosity is

$$L_{\nu\bar{\nu}} \sim 4\times 10^{15}\,(T_9^{\rm Schw})^9\,(4\pi\, r_{\rm s}^3/3)\,{\rm erg/sec} \approx 5\times 10^{57}(M_5^{\rm HC})^{-3/2}\,{\rm erg/sec}. \quad (2)$$

About 70% of the neutrino emission will be in the $\nu_e\bar{\nu}_e$ channel (Woosley, Wilson & Mayle 1986).

This ample $\nu\bar{\nu}$ emission can create a fireball above the core through $\nu\bar{\nu} \rightarrow e^+e^-$. The neutrino luminosities will undergo gravitational redshift, which depresses energy deposition above the star; however, this will be compensated by increased $\nu\bar{\nu}$-annihilation from gravitational bending of null trajectories (Cardall & Fuller 1997). The neutrino emission is nearly thermal (Shi & Fuller 1998), allowing the neutrino energy deposition rate to be approximated as

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

The total energy injected into the fireball above a radius r by this process is

$$E_{\rm f.b.}(r) = t_{\rm s}\int_r^{\infty} 4\pi r^2 \dot{Q}_{\nu\bar{\nu}}(r){\rm d}r \sim 2.5\times 10^{54}\,(M_5^{\rm HC})^{-3.5}(r_{\rm s}/r)^5\,{\rm erg}. \quad (4)$$

This is an unequivocally large amount of energy. For a star where $M_5^{\rm HC} = 0.5$, the energy of the fireball will be $\sim 10^{53}$ erg at a radius $r \sim 3r_{\rm s} \sim 10^{11}$ cm. This would correspond to the energy of a GRB with isotropic emission at a redshift $z \approx 3$.

2.2. Supermassive Star Cluster Collapse

The second venue for the production of a GRB fireball during supermassive black hole formation is the collapse of a star cluster of $10^5 - 10^9\,M_\odot$. The cluster undergoes a general relativistic instability (Shapiro & Teukolsky 1985) where collisions of $M_* \sim M_\odot$ stars could produce the neutrino emission powering a fireball. During the collapse, the stars will have relativistic speeds ($\Gamma \sim 1$) and a zero impact parameter collision of a pair will produce a typical entropy per baryon of $S \sim 10^4\Gamma^{1/2}(g_s/5.5)^{1/4}(M_\odot/M_*)^{1/4}(V_*/V_\odot)^{1/4}$ with $T_9 \sim 1$, and where $V_*/V_\odot$ is the ratio of the stellar collision interaction volume to the solar volume. Generally, the collisions will have a non-zero impact parameter, and involve the less dense outer layers of the star, where there will be larger entropies. These entropies could be high enough ($S \sim 10^7$) to produce the pair fireball without the need for neutrino heating. The complex structure and baryon-free regions between stars can provide areas for fireballs to form with low baryon-loading. Both the collisions and neutrino emission are stochastic processes which might lead to the complex time structure of GRBs.

3. Event Rates and the $\log N - \log P$ Distribution

If all collapses occur at a single redshift, z, the observed rate is

$$4\pi r^2 a_z^3 \frac{{\rm d}r}{{\rm d}t_0}\frac{\rho_{\rm b} F(1+z)^3}{M^{\rm init}}, \quad (5)$$

where r is the Friedman-Robertson-Walker comoving coordinate distance of the objects, a_z is the scale factor of the universe corresponding to z (with $a_0 = 1$), t_0 is the age of the universe, $\rho_{\rm b} \approx 2 \times 10^{-29}\, \Omega_{\rm b} h^2\, {\rm g\, cm^{-3}} \approx 5 \times 10^{-31} {\rm g\, cm^{-3}}$ (Tytler & Burles 1997) is the baryon density of the universe, h is the Hubble parameter in 100 ${\rm km\, s^{-1}\, Mpc^{-1}}$, and F is the fraction of all baryons in supermassive objects. With collapses occuring at $z \sim 3$ we have $r \sim 3000 h^{-1}$ Mpc, and the corresponding collapse rate is

$$0.15F\, (M_5^{\rm init})^{-1}\, {\rm sec}^{-1} \sim 10^4 F\, (M_5^{\rm init})^{-1}\, {\rm day}^{-1}. \tag{6}$$

With $F \sim 0.1\%$, and with a 100% detection efficiency, we will observe one collapse per day, assuming isotropic emission. This corresponds to a density of supermassive black holes of $7\, h^2/{\rm Mpc}^3$, about $350\, h^{-1}$ per L_* galaxy, or $\lesssim 10\, h^{-1}$ per galaxy-scale object (i.e. including dwarf galaxies).

It is instructive, however, to estimate the rate of supermassive object collapse in terms of numbers of Lyman limit systems and damped Lyα systems. Employing a column denisty $N_{\rm HI}$ distribution per unit column density per unit absorption distance of $10^{13.9} N_{\rm HI}^{-1.74}$ (Storrie-Lombardi, Irwin & McMahon 1996), the rate of supermassive object collapse will be comparable to that of GRBs if every Lyα system with $N_{\rm HI} \gtrsim 10^{18}\, {\rm cm}^{-2}$ experiences one supermassive object collapse.

The relation of the number of GRBs with peak flux ($\log N - \log P$) may be able to tell us something about the distribution of GRB sources in the universe. To see if there may be a correlation between this distribution and that of supermassive object collapse, we count the number of supermassive objects through the quasar population. That is, if quasars have some characteristic lifetime, then we can say that the comoving supermassive object number density is proportional to the comoving quasar number density. There has been some recent work in the evolution of the number density of quasars (Maloney & Petrosian 1998, Shaver et al. 1998). We use the evolution of quasar number to sum the number of supermassive collapse events for a standard candle and various cosmologies. The peak flux distribution calculated from supermassive object collapse is not inconsistent with the GRB $\log N - \log P$ relation, considering the uncertainties in the quasar epoch and GRB luminosity distribution. In Figure 1, we show the case for $\Omega_m = 0.25, \Omega_\Lambda = 0, \alpha = 0.7, z_{\rm th} = 3.4$, where α is the GRB spectral index, and z_{th} is the cutoff redshift of the BATSE detector. We must be careful, however, since the luminosity function of GRBs is unknown, and recent work has shown that this can affect the observed peak flux distribution greatly (Krumholz et al. 1998).

4. GRB Time Structure and Baryon Loading

The quickly varying time structure of GRBs limits the size of the region powering the fireball to the distance light can travel during this time variation, $\sim 10^7$ cm (Piran 1998). In the first venue described above of GRB production (supermassive star collapse) the characteristic size of the emission region in this spherically symmetric model is the Schwarschild radius, $\sim 10^{10}$ cm. The supermassive star's collapse and the formation of fireball(s) will not generally be spherically symmetric, nor will convective processes be unimportant. So, we

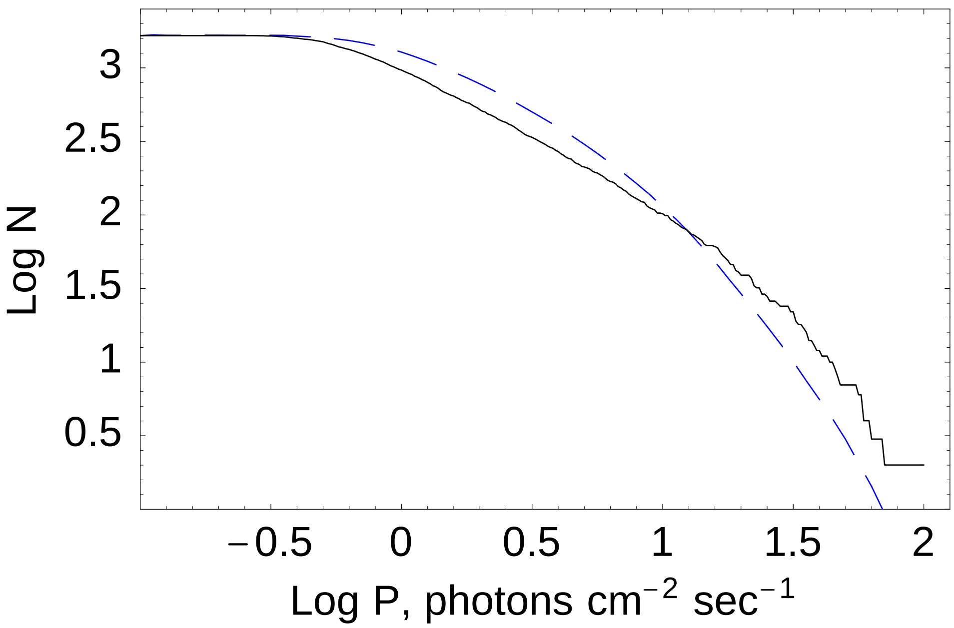

Figure 1. The BATSE 4B Catalogue number versus peak flux (solid) and the expected distribution (dashed) for supermassive object collapse associated with quasars. Here $\Omega_m = 0.25, \Omega_\Lambda = 0, \alpha = 0.7, z_{\rm th} = 3.4$.

can say that the above energy scales will be deposited and localized by neutrino annihilation into regions outside of the core that are a fraction of the core's size. These regions will be distributed around the core, and may produce variability through superpositions and instabilities. In the second venue, $1\,M_\odot$ stars have the same physical scale, $\sim 10^{10}$ cm, but can produce variability in the means described in §2.3 or through a localization of neutrino annihilation.

Producing a small region of high photon energy density and high entropy per baryon—the GRB fireball—is a challenge for all GRB models. The supermassive star model, in the one-dimensional case, also does not deposit the needed energies in a "baryon-free" region. However, if some of the tremendous energy deposited by the collapse does find itself in an area with low baryon density, it will produce a GRB fireball of large energies. This can happen when the star is rotationally flattened, where the neutrinos deposit their energy along the "baryon-free" axis of rotation.

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