

THE LONG AND THE SHORT OF GAMMA-RAY BURSTS

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ABSTRACT

We report evidence from the Third BATSE Gamma-Ray Burst Catalog that long ($T_{90} > 10$ s) and short ($T_{90} < 10$ s) gamma-ray bursts (GRBs) represent distinct source populations. Their spatial distributions are significantly different, with long bursts having $\langle V/V_{\max} \rangle = 0.282 \pm 0.014$ but short bursts having $\langle V/V_{\max} \rangle = 0.385 \pm 0.019$, differing by 0.103 ± 0.024 , significant at the 4.3σ level. This implies different spatial origin and physical processes for long and short bursts. Long bursts may be explained by accretion-induced collapse. Short bursts require another mechanism, for which we suggest neutron star collisions. These are capable of producing neutrino bursts as short as a few milliseconds, consistent with the shortest observed timescales in GRBs. We briefly investigate the parameters of clusters in which neutron star collisions may occur, and discuss the nuclear evolution of expelled and accelerated matter.

Subject headings: gamma rays: bursts — stars: neutron

1. INTRODUCTION

Kouveliotou et al. (1993) found that the durations of “classical” gamma-ray bursts¹ (GRBs) are bimodally distributed and are anticorrelated with their spectral hardness as measured by BATSE in the 50–300 keV band. These authors and Mao, Narayan, & Piran 1994 found no statistically significant differences between the spatial distributions of long and short GRBs.

Little attention has been paid to the cause of the division of GRBs into two classes, long and short. The simplest interpretation is that all GRBs are of similar origin, but have different values of one or more bimodally distributed parameters (for example, the interstellar density [Katz 1994a] or the shock parameters [Sari & Piran 1995]). Most models of GRBs have several poorly determined parameters. The observed anticorrelation of duration with spectral hardness is naturally obtained in the neutrino-fireball-debris-shock process (Rees & Mészáros 1992; Mészáros & Rees 1993; Katz 1994a), in which a higher Lorentz factor Γ leads to a shorter GRB and to a higher characteristic synchrotron frequency ν_{synch} .

The most popular neutrino-fireball-debris-shock models have been based on coalescing neutron stars (Eichler et al. 1989). However, in gravitational radiation-driven coalescence of a binary star the velocity of convergence of the stars is subsonic with respect to their interior sound speed. Unless the viscosity is spectacularly large ($\sim 10^{29}$ g cm⁻¹ s⁻¹), the flow is nearly adiabatic, with little heating or neutrino emission. The only strong shock would occur where a mass transfer stream strikes an accreting star or disk, a process which does not occur for stars of similar mass and radius, as in a neutron star binary. Three-dimensional hydrodynamic calculations (Janka & Ruffert 1996; Mathews et al. 1996) confirm this conclusion, which may also be inferred from the results of Davies et al. 1994; there is not enough heating or neutrino emission to create a sufficiently energetic fireball.

Accretion-induced collapse (AIC) of a bare degenerate dwarf has been calculated (Dar et al. 1992) to produce sufficient neutrino flux to power a fireball. AIC produces a ~ 10

s neutrino burst, as observed from SN 1987A (the presence of a stellar envelope turns the neutrino energy into a supernova, while its absence permits a relativistic fireball). The duration of neutrino emission is a lower bound on the duration of the resulting GRB because the subsequent shock interaction, particle acceleration, and radiation can stretch the observed GRB (as will the cosmological redshift), but cannot so readily shorten it. We note that AIC is much more frequent than GRBs, which require that the collapse be surrounded by the right density of matter to produce a relativistic baryonic shell. In other environments AIC may lead to undetected weaker GRBs or to analogous events with softer spectra.

AIC can therefore explain only long GRBs with $T_{90} > 10$ s; shorter GRBs require a different process. Both long and short GRBs must occur at “cosmological” distances (great enough that the geometry of space is non-Euclidean or cosmological evolution is significant) because each class is isotropically distributed on the sky and has $\langle V/V_{\max} \rangle < 0.5$ (Kouveliotou et al. 1993). Both probably produce soft (< 1 MeV) gamma rays by the neutrino-fireball-debris-shock process, explaining their qualitatively similar soft gamma-ray spectra and complex pulse forms, but the origins of the energy must be different.

The purpose of this paper is to investigate the hypothesis that long and short GRBs have different physical origins. In § 2 we compare their spectra at soft and harder gamma-ray energies. In § 3 we compare their distributions in space, and find a quantitative difference, although both classes are at “cosmological” distances. These two independent conclusions each confirm our hypothesis that short and long GRBs are the result of different events. AIC is discussed in § 4 as the origin of long GRBs. Short GRBs require a new process, for which we suggest colliding neutron stars in § 5. The nuclear composition of expelled and accelerated matter, and its implications for GRBs, is briefly estimated in § 6. Section 7 contains a general discussion.

2. SPECTRAL BEHAVIOR

If long and short GRBs are produced by two distinct kinds of events, members of these two classes may have qualitatively different spectral properties. This hypothesis can be tested with data in the Third BATSE Gamma-Ray

¹ This paper does not discuss soft gamma repeaters.

Burst Catalog (3B Catalog; Meegan et al. 1996). We find some evidence for qualitative differences between the spectral properties of long and short GRBs, although it is difficult to assess the contributions of selection effects and bias.

The BATSE hardness ratio is a measure of the spectral slope in the range 50–300 keV. Some of the bursts in the 3B Catalog were also detected by COMPTEL, EGRET, and OSSE, indicating the presence of energetic photons above the BATSE band. The data are summarized in Table 1. The choice of a BATSE hardness ratio criterion of 10 in the first line of the table selects the very hardest BATSE spectra, but is necessarily arbitrary. This was a natural choice when we first scanned the data by eye, and we have retained it.

Long and short GRBs appear to differ qualitatively. Considering only the BATSE and COMPTEL detections, the probability of this distribution (or of a greater difference between short and long GRBs) being obtained from a single population of events would be less than 10^{-8} were there no bias. The EGRET detections strengthen this conclusion, while the two OSSE detections contribute little information.

Unfortunately, two kinds of bias cloud this conclusion. BATSE detections are based on counts recorded over integrations of 1.024 s (or less), while COMPTEL detections are fluence limited up to durations of about 50 s (Kippen 1995). This introduces a strong bias in favor of COMPTEL detection (as compared to BATSE detection) of long GRBs over short GRBs; this bias is hard to quantify because long GRBs typically consist of several shorter subpulses, with a duty cycle significantly less than unity. The ratio of long to short GRBs detected by BATSE is about 3:2, but a fluence-limited detector would find a much larger ratio, probably between 5:1 and 10:1. The predominance of long GRBs in COMPTEL detections may only be a consequence of this effect, a conclusion supported by the COMPTEL spectra (Kippen 1995), which resemble extrapolations of BATSE spectra to higher photon energy rather than the onset of a new physical process. A similar bias may apply to EGRET detections (which do require a new physical process; Katz 1994b), and which in any case are too few to give a statistically significant result.

The predominance of short GRBs among those with BATSE hardness ratios greater than 10 may also be the result of bias. Near the detection threshold (as most GRBs

are), long GRBs usually have much higher fluence than short GRBs because of their continuing emission after the 1.024 s integration used in BATSE's threshold. Hence the statistical noise in the cumulative counts is greater for short GRBs than for long GRBs, even when each is just above the BATSE threshold. This statistical noise is likely to be the origin of most or all of the GRBs with extremely high hardness ratio (> 10), explaining why these events are almost all short.

3. SPATIAL DISTRIBUTIONS

If long and short GRBs have distinct physical origins, they may have distinct spatial distributions, although this is not specifically predicted. Table 2 presents the results of an analysis of the C/C_{\min} data in the 3B Catalog (Meegan et al. 1996). The whole catalog analysis shows that values of $\langle V/V_{\max} \rangle$ for long and short GRBs differ by 4.3σ , which is very unlikely to be a statistical fluctuation. Long and short GRBs are thus found to have different spatial distributions, consistent with their origins in different classes of events. This conclusion is also consistent with that of Cohen, Kolett, & Piran (1994) that long and short GRBs are detected to different limiting redshifts.

We analyzed the positional data in the 3B Catalog separately for long and short GRBs and found no statistically significant dipole or quadrupole deviations from isotropy for either class (confirming the result of Kouveliotou et al. 1993). We conclude that both classes are at “cosmological” distances, but that long GRBs are more deficient in faint bursts. This may reflect differences in the cosmological evolution of the two source populations.

C. Kouveliotou (1995, private communication; see also Mao et al. 1994) suggested that we subdivide the data on the basis of integration times, as shown in Table 2. This shows that small $\langle V/V_{\max} \rangle$ is chiefly a property of the subpopulation of smoothly rising GRBs (most of which are also long), which are defined by the criterion that they do not trigger the detector when short integration times (64 ms) are used. We can predict that if these “smooth risers” could be separated from other long GRBs, they would have even smaller $\langle V/V_{\max} \rangle$ and would be a pure AIC population, uncontaminated by GRBs which have an intrinsically short timescale (and hence rapid rise) but whose T_{90} is long because they radiate slowly or have multiple widely separat-

TABLE 1
BATSE HARDNESS AND HIGHER ENERGY DETECTIONS

Parameter	$T_{90} < 10$ s	$10 \text{ s} < T_{90}$
BATSE hardness ratio > 10 (0.05–0.3 MeV).....	21	1
COMPTEL detections (1–30 MeV)	4	20
OSSE detections (0.06–10 MeV)	0	2
EGRET detections (20–30,000 MeV)	0	6

NOTE.—Nominal sensitivity ranges are indicated. Data are from the 3B Catalog.

TABLE 2
 $\langle V/V_{\max} \rangle$ FOR SHORT AND LONG GRB DATA FROM 3B CATALOG

Burst Length	Whole Catalog	64 ms Data	256 ms Data	1024 ms Data
$T_{90} < 10$ s.....	0.385 ± 0.019	0.383 ± 0.021	0.373 ± 0.027	0.391 ± 0.022
$T_{90} > 10$ s.....	0.282 ± 0.014	0.370 ± 0.018	0.305 ± 0.017	0.276 ± 0.014
Difference	0.103 ± 0.024	0.013 ± 0.028	0.069 ± 0.032	0.114 ± 0.026

ed subpulses. Individual identification of “smooth risers” would require the complete time history of each GRB and would be difficult because of the limited signal-to-noise ratio of most GRBs.

4. LONG GAMMA-RAY BURSTS

Any model of long GRBs must explain their greater than 20 MeV emission, as observed by EGRET, by a process distinct from that which produces their lower energy emission. Such a model was developed (Katz 1994b) for the extraordinarily intense burst 3B 940217, which was very long ($T_{90} = 150$ s) as measured by BATSE and which also produced photons of energies as high as 18 GeV one hour after the initial burst (Hurley et al. 1994), but which had the unremarkable BATSE hardness ratio of 3.83. In this model the energetic gamma rays are attributed to π^0 decay or to Compton scattering by energetic electrons and positrons (themselves produced by π^\pm decay) resulting from relativistic nuclei (fireball debris) colliding with baryons in a dense cloud of circumfireball matter. We now suggest that such a model is applicable to many or all long GRBs (but perhaps not to short GRBs), although the density and geometry of the cloud will necessarily vary from event to event, as will therefore the efficiency of production of energetic gamma rays.

The cloud was attributed to excretion by the progenitor of one of the neutron stars in a coalescing neutron star model. That specific scenario must be replaced by one of AIC: when matter flows into an accretion disk surrounding the degenerate dwarf, a fraction f of it is excreted from the disk and the binary. This is inevitable; matter accreting onto the dwarf must give up nearly all its angular momentum, which flows outward by viscous stress in the accretion disk. Conservation of angular momentum gives

$$f = 1 - (r_{\text{RCR}}/r_{\text{LSO}})^{1/2}, \quad (1)$$

where r_{RCR} is the Roche circularization radius (Katz 1973) and r_{LSO} is the radius of the last stable disk orbit (Bahcall et al. 1974), from which mass peels off the disk and is lost; $f \approx 0.5$, almost independent of the binary mass ratio.

The circumfireball cloud must be rather small ($< 10^{15}$ cm) in order to be dense enough for collisional interaction with the relativistic debris. For energetic collisional gamma rays detected simultaneously with a 30 s GRB the time of flight suggests a size $\sim 10^{12}$ cm, but this may be an underestimate (by a factor up to Γ^2) if the relativistic particles are moving radially outward at the time of collision; as a result, the time of flight may not give a useful bound on the cloud dimensions. However, the requirement of collisional interaction gives a secure lower bound to the density and therefore, for reasonable cloud masses, an upper bound to the cloud's dimensions, independent of any assumptions about relativistic kinematics.

A degenerate dwarf cannot accrete hydrogen-rich matter at a rate faster than $3 \times 10^{-7} M_\odot \text{ yr}^{-1}$ because the Eddington limit bounds its thermonuclear luminosity. As a result, AIC is likely to be preceded by a period of accretion of the order of the Eddington time (Katz 1987),

$$t_E = \frac{\epsilon \kappa}{4\pi G} \approx 3 \times 10^6 \text{ yr}, \quad (2)$$

where ϵc^2 is the thermonuclear energy release per gram and κ is the opacity. It is not known how close to the Chandra-

sekhar limit the degenerate dwarf is when it begins accretion, but known degenerate dwarfs are at least a few tenths of a solar mass below that limit, implying accretion over at least $\sim 10^6$ yr.

Even the largest possible cloud is much too small to be freely expanding over an accretion time of $\sim 10^6$ yr. It could be gravitationally bound in an excretion disk outside the binary orbit, although it is not known how long such a disk would survive. Alternatively, accretion of helium or carbon-oxygen matter could proceed much faster because of the reduced thermonuclear energy release, efficient neutrino cooling (in burning of carbon and heavier elements), and the difficulty of igniting these fuels. Accretion of heavier elements resembles degenerate dwarf coalescence more than conventional mass transfer, and might be rapid enough (gravitational radiation-driven coalescence lasts ~ 30 yr) that escaping matter would still be sufficiently close and dense when the final collapse occurred, even if it were freely escaping.

Apart from their gamma-ray emission, such events might roughly resemble supernovae, as energy deposited in the cloud is thermalized and radiated. If classed as supernovae, they may be of unusual type and subtypical luminosity and duration (because the cloud is probably less massive than typical supernova envelopes). The predicted gravitational wave emission of a long GRB, produced by AIC, is $\sim 10^{-9} M_\odot c^2$ (Katz 1980; Burrows & Hayes 1996), or even less if no matter is expelled.

5. SHORT GAMMA-RAY BURSTS

Short GRBs require a new mechanism. The requirement of producing $\sim 10^{51}$ ergs of soft gamma rays, and $\sim 10^{53}$ ergs of neutrinos if the neutrino-fireball-debris-shock process is assumed, points to a catastrophic event involving one or more neutron stars; half the energy must be released in 10 ms in at least a few GRBs. We suggest the collision of two neutron stars, probably occurring in a very dense cluster of stars.

5.1. Colliding Neutron Stars

Unlike a mass transfer binary, colliding neutron stars will not generally be surrounded by a massive cloud. Any such cloud would probably be dispersed when the neutron stars were born; if not, it would rapidly be disrupted in a dense star cluster. Hence collisional production of pions and high-energy gamma rays is not expected from short GRBs, consistent with the rarity of their detection by COMPTEL and the absence of their detection by EGRET or OSSE.

Colliding neutron stars move on nearly parabolic orbits before collision. For masses of $1.4 M_\odot$ and typical equations of state (Wiringa, Fiks, & Fabrocini 1988) they have velocities (with respect to their center of mass) of $\approx 0.62c$ at contact, normally directed in a head-on collision. This is mildly supersonic in matter with the typical mean neutron star density $\rho_{\text{ns}} \approx 7 \times 10^{14} \text{ g cm}^{-3}$, for which these equations of state yield a sound speed $\approx 0.45c$. The resulting shock, requiring a supersonic velocity of convergence not found in coalescing binary neutron stars, is nature's way of making the large dissipation required for a GRB from a small viscosity.

The collision of two neutron stars is a very complex process, involving a strongly nonideal equation of state, three-dimensional (unless the collision is head-on) hydrodynamics, and significant effects of general relativity.

However, a rough estimate may be useful. The potential energy density attributable to the encounter is $GM\rho_{\text{ns}}/s$, where M is the mass of each neutron star and s is a mean separation. The internal energy of a shock-heated neutron star interior is $(11/4)aT^4$ if only photon and electron and muon neutrino (and antineutrino) specific heats are considered. This yields an underestimate of the internal energy, for it neglects the contributions of all charged particles, but is unlikely to be far wrong: the high Fermi energies of neutrons and electrons reduce their specific heats significantly from their nondegenerate values and limit the production of electron-positron pairs; protons are scarce; and muons are massive enough that comparatively few are produced.

If, in addition, we neglect the increase in density upon collision and the fraction of the energy release which appears as adiabatic compression of the degenerate matter rather than as thermal energy, we can equate the available and thermal energy densities:

$$\frac{GM\rho_{\text{ns}}}{s} = \frac{11}{4} aT^4. \quad (3)$$

For $M = 1.4 M_{\odot}$, $\rho_{\text{ns}} = 7 \times 10^{14} \text{ g cm}^{-3}$, and $s = 2 \times 10^6 \text{ cm}$ (corresponding to first contact in the absence of tidal distortion), we find $k_B T \approx 115 \text{ MeV}$. Some of our approximations tend to cancel, but most are in the direction of overestimating T . The fourth power makes equation (3) forgiving when T is being estimated, so it is probably fair to assume an initial postcollision temperature $k_B T_0 \approx 100 \text{ MeV}$.

The postcollision configuration has enough energy to recreate its initial state of two neutron stars with zero velocity at infinity. The collision redistributes energy, so that some matter may escape with finite speed v at infinity, leaving the remainder bound in a single object (which may promptly collapse to a black hole). We take a mass M_e expelled into a solid angle $\hat{\Omega} \leq 4\pi \text{ sr}$, beginning from a region of size r_0 at temperature T_0 .

At first this expelled matter is opaque to neutrinos because of its high density and temperature. We estimate its neutrino diffusion time $t_{\text{diff}} \approx 3r^2\rho\sigma/(m_H c)$, where $\sigma \approx 1.7 \times 10^{-38} (k_B T/100 \text{ MeV})^2 \text{ cm}^2$ is a mean neutrino interaction cross section (Janka & Ruffert 1996) and m_H is the nucleon mass. Adopting $\rho \approx 3M_e/(\hat{\Omega}r^3)$ and using the adiabatic cooling law for a relativistic gas of photons and neutrinos, $T \propto \rho^{1/3} \propto r^{-1}$, we equate t_{diff} to the hydrodynamic expansion time r/v to estimate the radius r at which most of the internal energy is radiated as neutrinos. The result is

$$r \approx 5 \times 10^7 \left(\frac{3 \text{ sr}}{\hat{\Omega}} \right)^{1/4} \left(\frac{v}{10^{10} \text{ cm s}^{-1}} \right)^{1/4} \left(\frac{M_e}{0.3 M_{\odot}} \right)^{1/4} \times \left(\frac{k_B T_0}{100 \text{ MeV}} \right)^{1/2} \left(\frac{r_0}{10^6 \text{ cm}} \right)^{1/2} \text{ cm}. \quad (4)$$

Equation (4) defines the radius at which the neutrinos escape the matter. The escaping neutrinos make a relativistic pair fireball in near-vacuum outside the expelled matter. Using standard results for the $\nu\nu \rightarrow e^+e^-$ cross section (Dar et al. 1992) and the previously estimated temperature ($k_B T \sim 2 \text{ MeV}$) and mean neutrino energy ($\sim 6 \text{ MeV}$) yields a neutrino-neutrino optical depth $\sigma_{\nu\nu} N_{\nu}/(\pi r^2) \sim 0.4$, where $N_{\nu} \sim 10^{58}$ is the total number of escaping neutrinos. While this is no substitute for a quantitative three-dimensional radiation-neutrino-hydrodynamic

calculation, it suggests that enough of an assumed 10^{53} ergs of neutrinos may be converted to pair plasma to power a 10^{51} erg GRB.

The neutrino pulse width $\sim r/(2v) \approx 2.5 \text{ ms}$ is a lower bound on the duration of the ultimate GRB. This result is consistent with observed GRB durations and is not far from the shortest timescales observed in GRBs; both these facts support this model of the physical processes in short GRBs.

A simple estimate shows that the gravitational radiation emitted in the collision of two neutron stars is $\sim 10^{-2} GM^2/r \sim 10^{51}$ ergs, into a broad band around $\sim 3 \text{ kHz}$. Its wave train would be very different from that of the gravitational radiation produced by coalescing neutron stars.

5.2. Clusters of Neutron Stars

A cluster of radius R , containing N stars each with mass M and radius r_s , has an evaporation time

$$t_{\text{ev}} \approx \frac{200N}{\ln N} t_{\text{cr}}, \quad (5)$$

where $t_{\text{cr}} \equiv (R^3/GM)^{1/2}$ is the crossing time. The timescale for the cluster to evolve by collisions is

$$t_{\text{coll}} \approx \frac{R}{r_s} t_{\text{cr}}, \quad (6)$$

where the cross section, allowing for gravitational focusing and nearly parabolic orbits as the neutron stars approach each other, is

$$\sigma \approx r_s R/N \quad (7)$$

if $R/N \gg r_s$, a condition met in all clusters of interest. The total collision rate is

$$v_{\text{coll}} \sim \left(\frac{GM r_s^2 N^3}{R^5} \right)^{1/2} \sim 10^{19} \frac{N^{3/2}}{R^{5/2}} \text{ s}^{-1}. \quad (8)$$

Allowed parameter regimes are shown in Figure 1, in which the stars have been taken to be neutron stars. Relativistic instability is avoided if $\Omega \equiv GMN/(Rc^2) \lesssim 0.1$. The present upper bound (Meegan et al. 1995) on the repetition rate of GRBs is $\sim 10^{-8} \text{ s}^{-1}$. If N_s short GRBs were detected over a period t_{obs} with angular accuracy $\delta\theta \ll (4\pi)^{1/2}/N_s$ (so that accidental coincidences are negligible), repetition rates as small as $\sim (N_s t_{\text{obs}})^{-1}$ could be detected. This could be a much more stringent bound than that set by BATSE data, whose large positional uncertainties introduce a substantial background of accidental coincidences. Note, however, that an unknown fraction of neutron star collisions produce observable GRBs, so that v_{coll} may exceed the observed repetition rate of short GRBs.

It is unclear whether the cluster evolution time should be longer or shorter than the age of the universe. The evolution which produced the cluster must, of course, require no more than $\sim 10^{10} \text{ yr}$, but may be shorter than the evolution time of the GRB-emitting cluster itself (for example, if the earlier evolution involved collisions of less compact stars with larger cross sections). A long-lived (less dense) cluster may have produced GRBs for most of the age of the universe, and will do so for a very long time, but a certain fraction of shorter-lived clusters would be active at any given time. A good analogy is to globular clusters, which are observed with core collapse times both longer and shorter than the age of the universe. As a result, it is impossible to exclude any region of Figure 1 except those with $v_{\text{coll}} \gg 10^{-8} \text{ s}^{-1}$ or

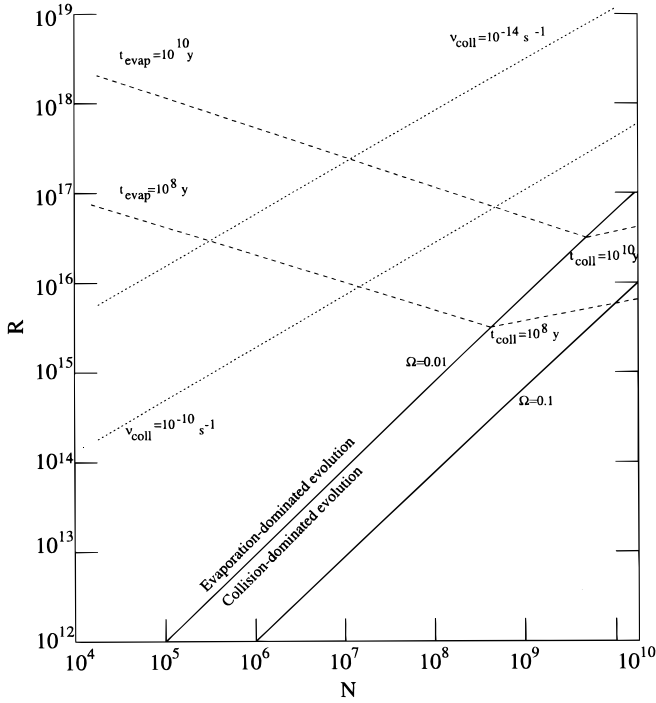


FIG. 1.—Parameter regimes for clusters of colliding neutron stars

$\Omega \gtrsim 0.1$. Clusters with high collision rates may permit the observation of repeating GRBs, but there is no a priori reason to expect this.

A hypothetical cluster with $N = 10^8$ and $R = 10^{18}$ cm (virial velocity $\approx 2 \times 10^8$ cm s $^{-1}$) has a collision rate $\sim 10^{-14}$ s $^{-1}$ and a lifetime of $\sim 10^{19}$ s. About 10^9 such clusters would be required to produce the observed 10^{-5} short GRBs s $^{-1}$ within $z \sim 1$; we cannot exclude the possibility that such clusters are commonly found at the centers of galaxies.

Dense clusters involving frequent collisions were discussed (Gold, Axford, & Ray 1965) as a possible origin of quasars, but this is now considered unlikely because stellar collisions do not obviously account for the nonthermal particle acceleration processes which are the essence of the active galactic nucleus phenomenon (GRBs are evidence, however, for particle acceleration in unexpected circumstances!). Quasar models make extreme demands on cluster parameters, for a quasar luminosity of 10^{46} ergs s $^{-1}$ requires a collision rate about 10^7 times that of our hypothetical cluster, if each collision releases 10^{53} ergs of observable energy (most of which is actually emitted as neutrinos rather than contributing to the electromagnetic luminosity of the AGN, widening the disparity). Cluster models intended to explain quasars were therefore very dense and suffered from short lifetimes or relativistic instability. The cluster parameters required to explain GRBs as the consequence of neutron star collisions are much less extreme, making such clusters more plausible.

Our hypothetical cluster would probably be undetectable at “cosmological” distances, except for its rare GRB activity. Its mean collisional luminosity, including neutrinos, is only $\sim 10^{39}$ ergs s $^{-1}$. Because the collision cross section and rate scale as the +1 power of the stellar radius (eq. [7]), and the specific binding energy as the -1 power, the collisional luminosity is roughly independent of stellar radius for a

cluster of specified R , N , and M . A cluster with similar values of these parameters, but less compact stars, would have a similar collisional luminosity but more frequent collisions and more rapid collisional evolution.

It is now considered likely that many galaxies possess massive black holes at their centers, which plausibly grew from dense clusters of stars. When the density becomes high, collisions become frequent, and lower density stars are disrupted, leaving only neutron stars and black holes. Dense clusters of evolved stars are plausible precursors to, or companions of, massive black holes; such a black hole has little effect on the structure of the cluster unless the black hole’s mass is dominant, a possibility we ignore (it increases the stellar velocities, and requires another parameter to describe it).

6. THERMONUCLEAR PROCESSING

In any neutrino-fireball-debris-shell model of GRBs, some material is accelerated from a dilute fireball above a neutrinosphere to make the relativistic debris shell. In AIC this material has very high entropy; a 10 s wind carrying $10^{-8} M_{\odot}$ from the surface of a neutron star has a density there of ~ 10 g cm $^{-3}$ but a temperature of ~ 1 MeV (Dar et al. 1992). A relativistic debris shell produced by a neutron star collision is formed under roughly similar fireball conditions, but may have a density $\sim 10^3$ g cm $^{-3}$ because its duration may be $\sim 10^{-3}$ s and its surface area of origin may be $\sim 10^{15}$ cm 2 (§ 5). Expelled neutron star debris, not accelerated to relativistic velocity, has much lower entropy, for it is shock-heated to $k_B T \sim 100$ MeV at $\rho \sim 10^{14}$ g cm $^{-3}$. Rather few baryons are accelerated in ultrarelativistic fireballs, but a much larger mass (perhaps $\sim 0.3 M_{\odot}$) of neutron star matter may be expelled at subrelativistic speed.

The nuclear composition of these several sources of matter is of interest. Temperatures of 1 MeV at densities $\leq 10^8$ g cm $^{-3}$ are sufficient to dissociate all nuclei to their constituent neutrons and protons, as will the much higher temperatures found behind shocks in neutron star interiors. The neutrino flux above a neutrinosphere is insufficient to equilibrate neutron and proton numbers in the time available ($\sim 10^{-4}$ s) in the accelerating flow (Weinberg 1972). In contrast, in a shocked neutron star interior with a black-body neutrino density at $k_B T \sim 100$ MeV, neutron-proton equilibrium will be achieved rapidly.

In either case, once the matter cools by adiabatic expansion, nucleosynthesis will begin. The problem resembles that of nucleosynthesis in the early universe, but with higher density and shorter timescales. At $k_B T \lesssim 100$ keV, equilibrium favors the reaction $p + n \rightarrow D + \gamma$, and unless the density is very low [$< (4 \times 10^4 t_{\text{exp}})^{-1}$ g cm $^{-3}$], where t_{exp} is the expansion time, all of the less numerous (of p or n) species will be bound as deuterons. Neutron beta decay is very slow, and the familiar network of reactions among p , n , D , T , and ^3He , which rapidly convert nearly all the D to ^4He , follows. The 3α reaction is too slow to be significant, so the products are almost entirely ^4He and either n or p . In contrast to the case of adiabatic decompression of neutron star matter (Eichler et al. 1989), no r -process or other heavy nuclei are produced.

The neutrons decay on a length scale (in the local observer’s frame) $\sim \Gamma c t_n$, where the neutron decay time $t_n \approx 1000$ s. For relativistic debris this may be comparable to the scale of shock interaction with the surrounding medium. Neutrons change this interaction. They run ahead of the shock

itself because they are not slowed by electromagnetic fields. Their decay introduces a stream of relativistic protons and electrons into the medium; this mix of counterstreaming charged particles is subject to plasma instabilities and, if equipartition is achieved, produces synchrotron radiation analogous to (and comparable to) that calculated in shock models of GRBs. The subsequent charged particle shock enters a relativistically preheated medium, and is weak.

7. DISCUSSION

Our choice of $T_{90} = 10$ s as the dividing line between long and short GRBs was made a priori, on the basis of the theoretically predicted duration of the neutrino burst from AIC (empirically supported by observations of neutrinos from SN 1987A). Our criterion differs from that (2 s) suggested by Kouveliotou et al. (1993). They chose this value because it is the observed minimum of the distribution of T_{90} . There are not many GRBs with $2 \text{ s} < T_{90} < 10 \text{ s}$. We found that these have $\langle V/V_{\text{max}} \rangle$ indistinguishable from those of even shorter GRBs, and that GRBs with $10 \text{ s} < T_{90} < 20 \text{ s}$ are indistinguishable from even longer GRBs. This supports our choice of a 10 s criterion. It is important, however, to define the division into long and short classes before analyzing the data (as we did), rather than searching for a criterion which maximizes the effect, which would make the error of using an a posteriori test of statistical significance.

The division of GRBs into two classes implies that statistical tests (for isotropy, repetitions, etc.) should be performed on each class separately. It is possible that members of each class may have different properties, even though all may radiate by the neutrino-fireball-debris-shock process, and effects which are statistically significant for one class may not be significant for the entire population. For example, we determined the angular autocorrelation function separately for long and short GRBs, in order to search for repetitions in each class of source without the statistical

interference of random coincidences with members of the other class, but found no statistically significant effect. We also searched for dipole and quadrupole anisotropy in each class, but again found no significant result.

Each of the models for GRBs discussed here probably implies a surrounding gas density, with which the relativistic shock interacts, much greater than the typical interstellar density $\sim 1 \text{ cm}^{-3}$ usually assumed. For long GRBs, a cloud of mass $0.3 M_{\odot}$ and radius 10^{15} cm has a mean density $\sim 10^{11} \text{ cm}^{-3}$, although out of the binary orbital plane it is likely to be much more dilute. The gas density within a dense cluster of neutron stars is difficult to estimate, but is increased above ordinary interstellar densities by accretion from the surrounding media and by tidal or collisional disruption of the occasional nondegenerate star that wanders into the cluster. The consequences of higher values of the gas density include shorter GRB pulses and more efficient conversion of the kinetic energy of relativistic debris to radiation.

$\langle V/V_{\text{max}} \rangle$ is smaller for long than for short GRBs. This implies that long GRBs are observed to greater distances than short GRBs. BATSE is several times less sensitive to long than to short GRBs (of a given fluence), implying that long GRBs are intrinsically ~ 10 times more energetic than short GRBs. This is consistent with our suggestion that long GRBs are surrounded by a higher density of gas than shorter GRBs, because the efficiency of radiation is predicted (Katz 1994a) to increase with gas density.

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