LA-UR-~~96~~- 97-1177

CONF-961266--2

TITLE: EXPANDING RELATIVISTIC SHELLS AND LIMITATIONS ON GAMMA-RAY BURST TEMPORAL STRUCTURE

AUTHOR(S): Edward E. Fenimore

SUBMITTED TO: Proceedings of the 18th Texas Symposium on Relativistic Astrophysics

Los Alamos NATIONAL LABORATORY

Limits on Expanding Relativistic Shells from Gamma-Ray Burst Temporal Structure

E. E. FENIMORE
Los Alamos National Laboratory, MS D436,
Los Alamos, NM 87544, USA

We calculate the expected envelope of emission for relativistic shells under the assumption of local spherical symmetry. Gamma-Ray Burst envelopes rarely conform to the expected shape, which has a fast rise and a smooth, slower decay. Furthermore, the duration of the decay phase is related to the time the shell expands before converting its energy to gamma rays. From this, one can estimate the energy required for the shell to sweep up the ISM. The energy greatly exceeds 10^{53} erg unless the bulk Lorentz factor is less than 75. This puts extreme limits on the "external" shock models. However, the alternative, "internal" shocks from a central engine, has one extremely large problem: the entire long complex time history lasting hundreds of seconds must be postulated at the central site.

The temporal structure of long complex Gamma-Ray Bursts (GRBs) presents a myriad of problems for models that involve a single central release of energy, as in many cosmological scenarios. Bursts with 50 peaks within 100 seconds are not uncommon, and there is the recent report[1] of a burst which might have lasted from 10^3 to 10^5 seconds. In Fenimore, Madras, & Nayakshin[2] (hereafter FMN), we used kinematic limits and the observed temporal structure of GRBs to estimate the characteristics of the gamma-ray producing regions. The bulk Lorentz factor of the shell, Γ, must be 10^2 to 10^3 in order to avoid photon-photon attenuation[3,4]. Since the emitting surface is in relativistic motion, the simple rule that the size is limited to $\sim c\Delta T$ does not apply. The high Γ factor implies that visible shells are moving directly towards the observer: if the material of the shell is a narrow cone, it is unlikely that the observer would be within the radiation beam yet outside the cone of material (see FMN).

Surprisingly, the curvature of the shell within Γ^{-1} is just as important in determining the envelope of emission as the overall expansion. This is understood by distinguishing the arrival time of the photons at the detector from the detector's rest frame time. We denote the former as T, and the latter as t. Assume the shell expands at velocity v and emits for time t. Because the emitting surface keeps up with the emitted photons, the photons will arrive at the detector within time $T = (c - v)t/c \approx t/(2\Gamma^2)$. In contrast, the curvature of the shell causes photons emitted from the material at angle $\theta = \Gamma^{-1}$ to arrive after the photons emitted on axis by $T = vt(1 - \cos\theta) \approx t/(2\Gamma^2)$. Thus, both the overall expansion (which might last 10^7 sec) and the delays caused by the curvature spread the observed signal over arrival times by about $t/(2\Gamma^2)$. Envelopes should, therefore, be estimated under the assumption of "local spherical symmetry": local because only $\theta \sim \Gamma^{-1}$ can contribute, symmetric because the material is seen head on, and spherical because curvature effects are important.

One can calculate the expected envelope of emission from an expanding shell. Let $P(\theta, \phi, R)$ give the rate of gamma-ray production for the shell as a function of spherical coordinates. Motivated by the "external shock" models[5], we assume a single shell, $R = vt$, which expands for a time (t_0) in a photon quiet phase and then emits from t_0 to $t_{\max}$ (i.e., $P(\theta, \phi, R) = P_0$ from $R = vt_0$ to $R = vt_{\max}$, and zero otherwise). In terms of arrival time, the *on-axis* emission will arrive between $T_0 = t_0/(2\Gamma^2)$ and $T_{\max} = t_{\max}/(2\Gamma^2)$. However, because the curvature is important, off-axis photons will be delayed, and most emission will arrive much later. The expected envelope, $V(T)$, is (see Eq. 11 in FMN):

$$V(T) = 0 \qquad \text{if } T < T_0 \qquad (1a)$$

$$= KP_0 \frac{T^{\alpha+4} - T_0^{\alpha+4}}{T^{\alpha+2}} \qquad \text{if } T_0 < T < T_{\max} \qquad (1b)$$

$$= KP_0 \frac{T_{\max}^{\alpha+4} - T_0^{\alpha+4}}{T^{\alpha+2}} \qquad \text{if } T > T_{\max} \qquad (1c)$$

where α is a typical number spectral index (~ 1.5) and K is a constant.

This envelope is similar to a "FRED" (fast rise, exponential decay) where the fast rise depends mostly on the duration of the photon active phase ($T_{\max} - T_0$) and the slow, power law decay depends mostly on the duration of the photon quiet phase. The decay phase is due to photons delayed by the curvature.

Often, GRBs do not have a FRED-like shape, implying that something must break the local spherical symmetry. Perhaps $P(\theta, \phi, R)$ is patchy on angular scales smaller than Γ^{-1}, with each patch contributing an observed peak. If so, we define the "filling factor", f, to be the ratio of the observed emission to what we would expect under local spherical symmetry (see Eq. 32 in FMN):

$$f = \frac{\int P(\theta, \phi, t)(1 - \beta\cos\theta)^{-3} dA}{\int (1 - \beta\cos\theta)^{-3} dA} \qquad (2)$$

Thus, we propose the "shell symmetry" problem for cosmological GRBs: models incorporating a single release of energy that forms a relativistic shell must somehow explain either how the material is confined to pencil beams narrower than Γ^{-1} or how a shell can have a low filling factor with a correspondingly higher energy requirement.

From Eq. 1, we find that the half-width of a GRB, $\sim T_{\rm dur}/2$, is $\sim T_0/5$. Thus the shell expands to about $R \sim 5\Gamma^2 T_{\rm dur}$ before becoming active. In previous work [5], the photon quiet phase was estimated from $E_0 = (\Omega/4\pi)R_{\rm dec}^3 \rho_{\rm ISM}(m_p c^2)\Gamma^2$ where E_0 is the energy required to sweep up the ISM with density $\rho_{\rm ISM}$, m_p is the mass of a proton, Ω is the total angular size of the shell, and $R_{\rm dec}$ is the radius of the photon quiet phase where the shell decelerates and begins to convert its energy to gamma-rays. (Note that one cannot solve E_0 for $R_{\rm dec}$ with an assumed Γ because R is related to Γ through the curvature effects.) Using $R = 5\Gamma^2 T_{\rm dur}$, we find that E_0 is an extremely strong function of Γ: $E_0 \sim 10^{32}\Gamma^8 T_{\rm dur}^3 \Omega \rho_{\rm ISM}$ erg. Unless E_0 is much larger than 10^{53} erg, Γ is quite small (~ 75) for bursts with $T_{\rm dur} \sim 100$ s.

Piran [6] has suggested that the filling factor is $\sim 1/N$, where N is the number of peaks in a burst, and that this filling factor is so small that it rules out single relativistic shells in favor of central engines. However, it is possible to create many peaks and have a large filling factor (as in Eq. 2) by allowing for variations in $P(\theta, \phi, R)$ (work in progress). Thus, we believe it is too premature to "rule out" single relativistic shells. Also, there are other ways to overcome inefficiencies. For example, Ω might be small.

Shaviv [7] has suggested that a single shell sweeps over a cluster of stars with each star contributing a peak to the time history. However, in such a scenario, T_0 is effectively zero so the envelope should have a rise that scales as T^2 (cf. Eq. 1), which is not often seen. In addition, the Shaviv model requires $\Gamma \sim 10^3$, so the energy to sweep up the ISM is extremely large: $10^{62}\rho_{\rm ISM}\Omega$. Globular clusters will have small $\rho_{\rm ISM}$, but not small enough. Other issues related to the time history and emission process have been raised by Dermer [8].

We conclude that GRBs do not show the signature of a single relativistic shell, and models must, therefore, explain how local spherical symmetry is broken enough to produce the chaotic time histories.

References

1. V. Connaughton, In Preparation.
2. E. E. Fenimore, C. D. Madras, and S. Nayakshin, *Ap. J.* **473**, 998 (1996).
3. M. G. Baring, *Ap. J.* **418**, 391 (1993).
4. S. Nayakshin and E. E. Fenimore, to be submitted, *Ap. J.*.
5. P. Meszaros and M. Rees, *Ap. J.* **405**, 278 (1993).
6. T. Piran, These Proceedings and R. Sari and T. Piran, Preprint.
7. N. Shaviv, These Proceedings and N. Shaviv and A. Dar, *Mon. Not. Royal. Astron. Soc.* **269**, 1112 (1995).
8. C. Dermer, submitted to *Ap. J.*.