Implications of Temporal Structure in GRBs

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The highly variable temporal structure observed in most GRBs provides us with unexpected clues. We show that variable GRBs cannot be produced by external shocks models and consequently cannot be produced by an “explosive” inner engine. The observed temporal structure must reflect the activity of the inner engine that must be producing unsteady and irregular “wind” which is converted to radiation via internal shocks.

Cosmological and even distant galactic halo GRBs models must overcome the compactness problem. Relativistic effects provide the only known solution to this problem. According to the generic picture, GRBs arise from a three stages processes: (i) A compact inner engine produces a relativistic energy flow (relativistic particles or electromagnetic Poynting flux - but not the observed photons) which (ii) transport the energy outwards to an optically thin region where (iii) it is converted to the observed radiation. Step (iii) could occur due to external shocks resulting from the deceleration of the energy flow into some external medium (e.g. the ISM). Alternatively, internal shocks that would arise in an irregular flow with non uniform velocities could convert the kinetic energy to radiation. We show here that internal shocks rather than external shocks convert the energy in GRBs.

Extensive efforts have been devoted to the question of how the observed spectrum is produced, probably because a single spectrum seems to be a universal characteristic of GRBs. The temporal structure, which varies drastically from one burst to another, was practically ignored until recently. Most bursts have a highly variable temporal profile with a rapid variability, on a time scale \( \delta T \ll T \), \( T \) being the burst’s duration. We suggest here that this temporal structure may provide the clue to this mystery.

The inner engine produces the energy flow which cannot be observed directly. The observed \( \gamma \)-rays emerge only from the outer energy conversion regions. This poses an additional difficulty in deciphering the origin of GRBs. Different engines could produce GRBs provided that they can produce the required relativistic energy flux. Variability on a time scale \( \delta T \) in the bursts dictates an upper limit to the size of this inner engine \( \sim c\delta T \). Inner engines can be “explosive” producing a single outgoing shell whose width \( \Delta \) is comparable to the size of the inner engine. An inner engine can also produce a “wind” an outgoing flows on scales longer than the size of the source. We show here that the observed temporal structure cannot be produced within the energy conversion regions and it must reflect the activity of the source.
Consequently “winds” rather than “explosions” power GRBs.

Consider a relativistic shell that converts its energy to radiation. Let $\Delta$ be the width of the shell and let the conversion take place between $R_E$ and $2R_E$. The emitting material moves with a Lorenz factor $\gamma$. There are three generic time scales. First is the difference in arrival time between two photons emitted at $R_E$ and $2R_E$, $T_R \approx R_E/\gamma^2 c$. Angular spreading, that is blending of emission from regions from an angle $\theta$ from the line of sight leads to a second time scale $T_\theta \approx R_E \theta^2/c$. Finally, $\Delta/c$ the light crossing time of the relativistic shell, corresponds to the time difference between the photons emitted from the shell’s front and from its back.

Examine now a very thin shell. A typical source that produces a thin shell is an “explosive” fireball for which the width of the shell is comparable to the size of the inner engine. However, sources that produce a short wind are also of this kind. Now more specifically require that the shell satisfies: $\Delta \leq R_E/\gamma^2$. It is remarkable that even arbitrarily thick shells will satisfy this conditions if the emission is due to external shocks. Since $\Delta < R_E/\gamma^2$ the duration of the burst is determined by the energy conversion region and not by the duration that the inner engine operates (which determines $\Delta$).

Because of relativistic beaming an observer detects radiation from an angular scale $\gamma^{-1}$ around the line of sight. Thus the angular size of the observed regions always satisfies $\theta \leq \gamma^{-1}$. If the system is “spherical” (that is spherical on a scale larger than $\gamma^{-1}$) $\theta \approx \gamma^{-1}$ and then $T_\theta \approx R_E/\gamma^2 c \approx T_R \approx T$. Thus angular spreading will erase all temporal structure on scales shorter than $T_\theta$ resulting in $\delta T \approx T$. In order to produce variable bursts with $\delta T \ll T$, within the external shock scenario, one must break the spherical symmetry on scales smaller than $\gamma^{-1}$.

It is useful to define a variability parameter $\mathcal{V} \equiv T/\delta T \sim 100$. Detailed analysis\footnote{Note that $\gamma$ could be smaller than the initial Lorentz factor of the shell.} shows that the emitting regions must have an angular size smaller than $(\gamma \mathcal{V})^{-1} \leq 10^{-4}$ to produce such a variability. A sufficiently narrow jet can bypass this restriction. But it is not clear how one can accelerate and collimate it. Hydrodynamic acceleration, for example, cannot produce an angular width smaller than $\gamma^{-1}$. A second possibility is an emitting region made of numerous small size bubbles. The number of bubbles (emitting regions) should be smaller than $\mathcal{V}$, otherwise the contribution from different bubbles will average out to a smooth signal. The maximal solid angle of each bubble is $(\gamma \mathcal{V})^{-2}$. Therefor the total solid angle of all bubbles is smaller than $(\gamma^2 \mathcal{V})^{-1}$, which is only $\mathcal{V}^{-1}$ of the observed solid angle. This leads to an intrinsic inefficiency in conversion of energy to radiation of magnitude $\mathcal{V}^{-1}$, ruling out models based on this idea.

\footnote{Strictly speaking this was shown only for hydrodynamic shocks.}
Let’s turn now to a wide relativistic shell in the form of a wind. If the wind is irregular the energy conversion would be due to internal shocks and the condition $T_R < \Delta/c$ would be satisfied. This will produce a burst whose overall duration is $\Delta/c$ and the observed variability scale is $\delta T \approx T_0 \approx T_R$. The variability scale could be much shorter than the duration. The duration is determined now by the activity of the inner engine and not by the emitting regions. The observed temporal structure reflects the activity of the inner engine, which must be producing a relatively long and highly irregular wind.

We find that only this second possibility, of a “wind” like inner engine and energy conversion by internal shocks, can produce the observed temporal structure. This conclusions have several direct implications. First it tells us that the emitting regions operate with the internal shock mechanism. This would have direct implications for any attempts to calculated the observed spectrum from these events. The implications for the inner engine are even more dramatic: It must operate for a long duration, up to hundred of seconds in some cases, and it must produce highly variable winds as required to form internal shocks and the observed variable activity. This directly rules out all explosive models. We will discuss elsewhere the implication of this conclusion for some specific models.

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This is provided, of course, that the cooling time is shorter than $T_\theta$.

In fact we have shown here that external shocks cannot produce the observed temporal structure. We have not shown yet that internal shocks can produce it. This work is in progress now.