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THE PROMPT EMISSION OF GAMMA-RAY BURSTS

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Abstract. Gamma-ray bursts are the brightest objects in the Universe. Their prompt emission, mostly in soft gamma-rays (from a few keV to a few MeV) is followed by an afterglow that can be detected for weeks and months and where the emitted radiation becomes progressively softer from X-rays to visible and finally radio wavelengths. The physics of both the prompt and afterglow phases is uncertain and especially the origin of the prompt emission remains highly debated. This review presents a short summary of the situation.

Keywords: Gamma-ray bursts, Relativistic hydrodynamics, Shocks, Radiation processes

1 Introduction

In spite of the temporal and spectral data that have now been accumulated for several thousands of bursts, there are still several distinct possibilities to explain the prompt phase. The origin of the energy and the acceleration mechanisms that power a relativistic outflow from the central engine, the dissipation (comptonization below the photosphere, internal shocks, magnetic reconnection) and radiation processes responsible for the observed emission are not fully understood.

2 Observational summary

2.1 Temporal properties

Gamma-ray bursts are characterized by a great diversity in duration and temporal behaviors. They are short events, but nevertheless the prompt phase covers an interval of six orders of magnitude in duration from a few milliseconds to several thousands of seconds. The distribution of duration is bimodal with two peaks at respectively 0.3 and 30 s (Kouveliotou et al. 1993). The short events are supposed to be associated to the merging of compact objects (two neutron stars or a neutron star and a black hole) while long ones come from the collapse of massive stars (at least one burst, GRB 030329 has been clearly found in coincidence with a type Ic supernova, i.e. the explosion of a Wolf-Rayet star; Stanek et al. 2003).

The light curves in the keV-MeV spectral range, where most of the energy is released, can generally be represented by a succession of elementary "pulses", with a fast rise and a slower decay. Some light curves are simple with just one or a few pulses, while others are extremely complicated with many overlapping pulses.

Only a few events have been captured in the optical during the prompt phase either by fast response cameras following an alert or simply by chance. Again, the behavior in the optical range can very much differ from one burst to another. In GRB 990123 the visible light curve exhibits a power law decline (Gisler et al. 1999) while in GRB 041219A and GRB 080319B it seems to (approximately) follow the variations seen at high energy (Vestrand et al. 2005; Beskin et al. 2010). But in GRB 041219A the optical flux fits well with an extrapolation of the spectrum at low energy while in GRB 080319B (the so-called "naked-eye burst") it is hundreds times brighter.

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2.2 Spectral properties

GRB spectra can be represented in first approximation by the phenomenological Band function, which is simply two smoothly connected power-laws of respective indices α and β at low and high energy. The distribution of α is approximately normal, centered at $\alpha = -1$, while values of β extend from -2 to -4, with an average at -2.5 (Preece et al. 2000). The break energy, which is also the peak of the spectrum in $E^2N(E)$ (where $N(E)$ is the number of photons per unit energy) corresponds to the typical energy of photons that carry the bulk of the burst power. The distribution of the peak energy is approximately log-normal with a maximum at about 200 keV (Preece et al. 2000).

Recent results obtained with the GBM instrument onboard *Fermi*, which has an excellent spectral coverage, allow to go beyond the Band function and have identified in a few events a possible underlying thermal contribution below the broken power-law main component (Guiriec et al. 2011). In some cases an additional power-law, apparently extending from low energy (10 keV) to very high energy (100 MeV) is also detected (Ackermann et al. 2010).

3 Models

3.1 Basic requirements

When, following the discovery of the afterglows by the Beppo-SAX satellite in 1997 the first redshifts were measured (Metzger et al. 1997), it appeared that GRBs were located at cosmological distances (the largest confirmed redshift now exceeds $z = 8$!) which implied that the sources were able to release in a few seconds from 10^{51} to 10^{54} erg (assuming isotropic emission). Since the observed light curves sometimes vary on time scales as short as a few milliseconds, it also implied that the sources had to be compact. The resulting photon density is therefore huge and because GRB spectra often extend beyond 511 keV, extensive pair creation could be expected, leading to a very large Thomson opacity. The spectra show no evidence of that and the classical solution of this so-called "opacity problem" (first discussed in the context of radio sources by M. Rees in 1966) is to suppose that the radiation is emitted by material moving at relativistic velocities towards the observer. Then, the energy of the observed photons is reduced by the Lorentz factor Γ of the flow in the frame of the emitting material, while in the observer frame the photons are affected by relativistic beaming and move on quasi-parallel trajectories, which strongly raises the photon annihilation threshold. The constraints on the Lorentz factor depend on the burst spectrum and emitted power but typically a minimum $\Gamma_{\rm min} \sim 100$ appears necessary, with $\Gamma_{\rm min}$ possibly reaching 1000 in the most extreme cases (for example for events detected by Fermi/LAT and producing GeV photons; Lithwick & Sari 2001; Hascoët et al. 2012b).

3.2 Acceleration of the flow

The central source must therefore be able to accelerate the flow to ultra-relativistic velocities, which is not an easy task, especially in long GRBs where the progenitor is supposed to be a massive Wolf-Rayet star whose core is collapsing to a black hole, so that the outflow has to drill its way out of the stellar envelope. Two possible mechanisms have been considered to accelerate the flow:

- Thermal acceleration: energy is injected at the base of the flow in thermal form; this would be the case if the source of energy is $\nu\bar{\nu}$ annihilation of neutrinos emitted by the hot accretion torus surrounding the black hole (Zalamea & Beloborodov 2011). The hot plasma then adiabatically expands. The Lorentz factor first increases proportionally with radius until it reaches a final value $\Gamma_{\rm f} = E_{\rm th}/Mc^2$, where $E_{\rm th}$ is the injected thermal energy and M the amount of mass entrained in the flow (Piran 1999).

- Magnetic acceleration: in this case the flow is initially magnetically dominated and the acceleration occurs via a direct transfer of magnetic into kinetic energy. The acceleration is slower than in the previous case going as $R^{1/3}$ (at least in the simplest models; Drenkhahn & Spruit 2002). An important question concerns the amount of residual magnetization at infinity $\sigma_\infty = e_{\rm mag}/e_{\rm K}$ where $e_{\rm mag}$ and $e_{\rm K}$ are respectively the magnetic and kinetic energy densities (see 3.3.2 below).

3.3 Dissipative processes

3.3.1 Below the photosphere

GRBs are observed because part of the thermal, kinetic or magnetic energy of the outflow is converted into radiation. In photospheric models, the observed luminosity is supposed to come directly from the photosphere when the trapped thermal energy is eventually released where the optical depth of the expanding flow goes below unity. An obvious difficulty is that the resulting spectrum should be close to a blackbody. A solution to this problem is to consider that dissipative processes occur below the photosphere at optical depths of a few (Rees & Mészáros 2005; Beloborodov 2010). Several possible processes have been considered: (i) neutron-proton collision if neutrons decoupled from the flow before it has been fully accelerated so that protons and neutrons have different terminal Lorentz factors (ii) shocks or (iii) reconnection if the flow is magnetized. All these processes ultimately produce energetic electrons that can undergo inverse Compton collisions with the thermal photons. This can transform the spectrum, replacing the exponential cut-off of the Planck function by a power-law tail.

3.3.2 Above the photosphere

Dissipative processes can also occur above the photosphere. The most extensively studied possibility is the restitution of a fraction of the flow kinetic energy through internal shocks between shells moving at different Lorentz factors. An alternative consists to again invoke reconnection if the ejecta is magnetized, as it can happen either below or above the photosphere.

- Internal shocks: the general idea of internal shocks is vey simple. It supposes that the distribution of Lorentz factor in the flow is not uniform so that shells with high Lorentz factors are able to catch up and collide with slower ones (Kobayashi et al. 1997; Daigne & Mochkovitch 1998). For example, the relative velocity of two shells moving respectively at $\Gamma_1 = 100$ and $\Gamma_2 = 300$ is $v_{\rm rel} = c\,(\Gamma_2^2 - \Gamma_1^2)/(\Gamma_2^2 + \Gamma_1^2) = 0.8\,c$. When they collide, the dissipated energy is used to accelerate electrons and amplify the magnetic field. The electrons then lose energy by emitting synchrotron (and inverse Compton) radiation, which is responsible for the observed flux. Internal shocks can however form only if the residual magnetization of the flow is small ($\sigma_\infty < 0.1$) which, in the case of magnetic aceleration, supposes that magnetic energy has been almost completely converted into kinetic energy.

- Reconnection: in reconnection models, which are well suited to the case where $\sigma_\infty > 0.1$, the energy released by reconnection accelerates electrons that again emit synchrotron radiation. These models are still in their infancy due to the complications of the physics of reconnection. The most elaborated one is the ICMART (Internal-Collision-induced MAgnetic Reconnection and Turbulence) model, that in some way couples internal shocks and reconnection (Zhang & Yan 2011). Light curves can be calculated from ICMART but not yet spectra that could be compared to observed ones (Zhang & Zhang 2014).

3.4 Evaluating and testing the models

3.4.1 Pros and cons

Among the three models proposed to explain the prompt emission, internal shocks is the one which is the most easily calculable and therefore the one that makes the largest number of predictions. Many of them are in reasonable agreement with the data such as the various relations linking temporal and spectral properties (hardness-duration and hardness-intensity relations, evolution of pulse widths as a function of energy, etc, see Bošnjak & Daigne 2014, for details). But the internal shock model also faces several problems: (i) to get a peak of the synchrotron emission at a few hundreds keV, it appears necessary to transfer a large fraction of the shock dissipated energy to only a very small fraction of the electron population ($\sim 1\%$). Internal shocks are mildly relativistic, with the relative Lorentz factor of the colliding shells being typically between 1 and 2. Contrary to the ultra-relativistic case, this regime has not been explored by simulations, but transferring most of the shock dissipated energy to just a few electrons appears quite challenging; (ii) even if electrons can be properly accelerated, radiative efficiency requires that synchrotron emission should take place in the "fast cooling regime" (where the radiative time scale is short compared to the hydrodynamic time scale) but then the spectral index of the spectrum at low energy should be -1.5 while the average observed value is -1 (Ghisellini et al. 2000). Some possible solutions to this problem have been proposed but none appears fully satisfactory.

Photospheric and reconnection models make much less predictions than internal shocks. Especially in the case of reconnection, light curves (but not spectra) have been produced by only one group (Zhang & Zhang 2014), so that comparison to observation is very limited. Reconnection simply appears natural if the outflow keeps a large magnetization far from the source. The radiation process, as for internal shocks, is synchrotron with the same potential problems regarding the shape of the spectrum.

Photospheric models are favored if the acceleration of the flow has a thermal origin because of the large amount of energy that can be released at transparency. To transform the Planck spectrum into a broken power-law a sub-photospheric dissipation process is however necessary and a potential difficulty is that it has to work in a variety of regimes since, as a function of time during the prompt phase, the peak energy of the spectrum can vary by a factor of one hundred (and even more in some cases) with the photospheric radius also experiencing large changes.

3.4.2 Temporal tests

The X-ray light curve of the early afterglow of most GRBs obtained by the XRT instrument onboard *Swift* starts with a steep decay where the X-ray flux $F_X \propto t^{-3}$. A nice geometrical interpretation has been proposed for this behavior (Kumar & Panaitescu 2000). It may correspond to the signal from the last shell of the ejecta that has been illuminated at the end of the prompt phase. Due to the curvature of the shell, the radiation emitted by a surface element away from the line of sight reaches the observer with a delay. The calculation shows that the resulting behavior fits well with the observed decay, but only if the radius of the shell is large, as it is in models where dissipation takes place beyond the photosphere, the best agreement being obtained in the case of internal shocks (Hascoët et al. 2012a). In photospheric models the early steep decay cannot be explained by this geometrical effect and should therefore correspond to an effective behavior of the central engine.

3.4.3 Spectral tests

The observation of an underlying thermal component in the spectrum a few GRBs by the GBM instrument onboard *Fermi* is very important if it is confirmed in the future. Indeed, the presence of such a component is a natural prediction of the internal shock and reconnection models while it is not expected in photospheric models (Hascoët et al. 2013). In the two former cases, the main spectrum is formed above the photosphere and the photospheric emission (with approximately a Planck shape) is produced independently and simply adds its contribution to the total. In the latter case, what we see is the thermal contribution that has been modified by dissipative processes below the photosphere. One therefore does not expect that it will show up as an additional component in the observed spectrum.

Another possible test comes from the prompt optical emission when its appears correlated to the gamma-rays. This may suggest that both are produced at comparable radii. If this is the case, photospheric models might be in trouble, due to the risk of self-absorption that would cut-off the spectrum at low energy.

3.4.4 Polarization tests

Data from the IBIS instrument onboard INTEGRAL indicate a high degree of polarization in the prompt emission of some GRBs (Götz et al. 2009, 2013). These observations favor models with synchrotron emission (i.e. internal shocks or reconnection) under the additional condition that the magnetic field is ordered in the emission zone. In photospheric models the polarization averages to zero except if the jet is viewed on the edge or if there is a synchrotron contribution together with the photospheric one.

4 Conclusions

This short review has shown that many uncertainties remain about the origin of the prompt emission in gamma-ray bursts. All proposed models have virtues and drawbacks. We have presented some possible tests that can be used to discriminate among them. Spectral tests are promising as more and more spectra covering a broad range (from a few keV to 100 GeV) are being obtained by the two instruments (GBM and LAT) onboard the *Fermi* satellite. The development of polarimeters working in the hard X-ray domain will be also very useful to confirm and extend the results obtained by the IBIS instrument.

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