The fireball shock model of gamma-ray bursts

The energy of gamma-ray bursts at cosmological distances must be $E_0 \sim 10^{-3} - 1 M_\odot c^2$ if isotropic, and their variability timescales suggest an origin in a region of size $\lesssim 10^7$ cm. This will result in a fireball consisting of γ-rays, leptons and baryons [1, 2, 3], which will be optically thick and whose expansion will be relativistic if the baryon load is small. The expansion will convert most of the initial explosion energy into kinetic energy of the baryons, with an optically thick (black-body) gamma-ray luminosity of correspondingly lower total energy [4, 5].

External shocks.– The fireball shock model solved the problem of reconverting the kinetic energy of the baryons into radiation, while providing the conditions for the latter to have a non-thermal spectrum. The simplest form of this is in the *"external" shock* which must occur when the relativistic fireball ejecta has swept up a sufficient amount of external (e.g. interstellar) gas that its back reactions starts to slow down appreciable the ejecta [6] . It can be shown that for an ejecta of baryon mass M_{ej} and terminal Lorentz factor Γ_0 this occurs when the amount of swept up external mass is $M_{sw} \simeq M_{ej}/\Gamma_0$, at a deceleration radius given, from energy conservation, by

$$r_{dec} \sim (3E_o/4\pi n_{ext} m_p c^2)^{1/3} \Gamma_0^{-2/3} \sim 5 \times 10^{16} (E_{53}/n_{ext})^{1/3} \Gamma_{2.5}^{-2/3} \text{ cm} \tag{1}$$

where n_{ext} is the external baryon number density and E_0 is the isotropic equivalent burst energy. Particles scattered across the shock interface will be Fermi-accelerated to a relativistic power law distributions, and since the shock is optically thin at r_{dec} this leads to non-thermal synchrotron and IC radiation [7, 8]. The associated timescales are $t_{dec} \sim r_{dec}/(2c\Gamma^2) \sim 10(E_{53}/n_o)^{1/3}\Gamma_{2.5}^{-8/3}$ s.

Internal shocks.– For typical Lorentz factors $\Gamma \sim 300\Gamma_{2.5}$ the above timescales cannot reproduce the $10^{-3} - 10^{-1}$ s variability timescales observed in the prompt gamma-ray emission of many bursts. Shocks and flares in the accretion disk around central engine of size $\lesssim 10^7 - 10^8$ cm can produce such timescales [9, 10]. However, they occur below the outflow scattering photosphere $r_{ph} \sim 3\times \sim 10^{11} L_{52} \Gamma_{2.5}^{-3}$ cm, so if the radiation also occurs there the observed variability is smeared out. This was the motivation for introducing the *"internal" shock* model [11]. This is based on the fact that variability in the central engine or disk will lead to a variable fireball outflow energy or momentum rate, and e.g. if the Lorentz factor varies over times $t_v = 10^{-3} t_{v,-3}$ s shorter than the total duration, successive ejected sub-shells whose Lorentz factors differ by $\Delta\Gamma \sim \Gamma$, initially separated by ct_v, will catch up with each other at an internal shock (or dissipation) radius

$$r_{dis} \sim ct_v \Gamma^2 \sim 3 \times 10^{12} t_{v,-3} \Gamma_{2.5}^2 \text{ cm}. \tag{2}$$

These internal shocks are typically optically thin, since they are *above* the scattering photosphere, $r_{dis} > r_{ph}$ [11], and particles are again Fermi accelerated to a power law, emitting synchrotron and inverse Compton radiation. Here the observed variability reflects the variability of the central engine output, which for a body of dimensions $r_\ell \sim 10^7$ cm can be as short as milliseconds, as required by observations.

The external synchrotron-IC shock has been successful in explaining the main features of GRB afterglow, while the internal shock model is the most widely used for interpreting the prompt gamma-ray emission observations, e.g. [12, 13].

References

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