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A Bulk Comptonization Model for the Prompt GRB Emission and Evolution

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We propose that the process responsible for the GRB spectra in the MeV band is the bulk Comptonization of synchrotron photons produced within a relativistic blast wave (RBW) of Lorentz factor (LF) Γ, which scatter in the upstream medium and are then re-intercepted to be bulk Comptonized by the RBW. At the same time, these photons scatter also with postshock protons of energy $\Gamma m_p c^2$ via the reaction $p\gamma \to p e^+ e^-$, thereby converting proton energy into radiation. The peak in the GRB spectral luminosity at $E_p \simeq 1$ MeV, is just the energy of synchrotron photons produced by the e^+e^-−pairs of the above reaction, after their bulk Comptonization by the RBW *and their transformation to the observer's frame*. It has been shown that for postshock column densities greater than a critical value, the conversion of proton energy to e^+e^-−pairs is explosive and on time scales comparable to the postshock light crossing time. We show that, under such circumstances, the bulk Comptonization radiation reaction can decrease the RBW Γ to roughly half its value on distances much smaller than its deceleration distance. This leads to termination of the e^+e^-−pair production and a very steep drop in the resulting GRB flux; after this abrupt decrease, Γ and the much diminished GRB flux, remain constant to the deceleration distance imposed by the outside conditions, beyond which point they resume their more conventional decrease. This behavior is in agreement with the puzzling *Swift* observations of GRB afterglow light curves, which is thus attributed to the very process of the GRB photon production.

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1. Introduction

With the confirmation of the cosmological nature of GRB by *BeppoSAX* [1] and the ensuing general theoretical description of the resulting afterglows, it was generally considered that the salient features of the GRB radiation emission and time evolution were firmly established. It was therefore expected that the launch of *Swift* would provide the statistics of a large number of GRB that would confirm and refine this general paradigm. However, the *Swift* observations have instead led to a novel set of unanticipated problems, without providing obvious resolution to older ones: These were the peculiar dependence of the flux of a large fraction of GRB with time, i.e. the very steep decline ($\propto t^{-3} - t^{-6}$) of the XRT flux, followed by flux at roughly constant level, before resumption of its decline at the more or less conventional rates longer time scales [2]. This novel, little understood GRB afterglow behavior was added on the already open issues of GRB physics, namely: (a) the nature of their central engine (b) the process of converting the relativistic outflow energy into radiation (c) the reason for which the GRB spectra exhibit a spectral peak emission at an energy $E_p \simeq 1$ MeV.

In the past we have proposed a model that provides answers to points (b) and (c) above [3, 4, 5]. This model relies on a radiative instability incurring in plasmas with energy stored in form of relativistic protons: The instability is due to the production of e^+e^-–pairs in the reaction $p\gamma \to pe^+e^-$, with the newly formed pairs providing (via the synchrotron process) an increasing number of photons for interaction with the relativistic protons. As discussed in the above references, the crucial parameter for the presence of the instability is the column density of the postshock relativistic protons. This quantity determines what fraction of the synchrotron photons produced by each pair of the $p\gamma \to pe^+e^-$ reaction (with Lorentz factor Γ) will produce new pairs before its escape from the system. If the number of pairs produced by each electron is greater than 1, the situation is unstable, as each successive generation of pairs will produce more pairs, thus exponentially increasing the number of pairs and depleting the relativistic proton energy. A moment's thought indicates that the criticality condition is very similar to that of a nuclear pile, hence the nickname of this model.

In addition to the column criticality condition, there is also a criticality condition imposed by the threshold of the $p\gamma \to pe^+e^-$ reaction: each of the upstream reflected synchrotron photons when viewed on the frame of the relativistic protons much be sufficiently high to pair produce. As discussed in [3, 4, 5] this leads to the condition

$$b\Gamma^5 \gtrsim 2 \tag{1.1}$$

where $b = B/B_q$ is the magnetic field on the RBW normalized to the quantum critical field $B_q \simeq 4. \times 10^{13}$ G. One can now compute the energy of the synchrotron photons produced by these pairs (whose LF is Γ, the same as that of the RBW) *in the observer's frame*, after they reflect upstream of the RBW and then get bulk-Comptonized by it: The original synchrotron energy is $\varepsilon_s \simeq b\Gamma^2$; after upstream reflection and bulk Comptonization, the synchrotron photon energy has increased by two factors of Γ to $b\Gamma^4$, as viewed on the RBW frame; a final Lorentz boost to the observer's frame moves that energy to $b\Gamma^5$. Assuming that the burst operates near its threshold given by Eq. (1.1), the peak emission of the bulk Comptonized component is at the same energy as the kinematic threshold, i.e. 2 m_ec^2, in broad agreement with observation. Hence, within the confines of this model the observed value of E_p in GRB simply reflects the kinematic threshold of the

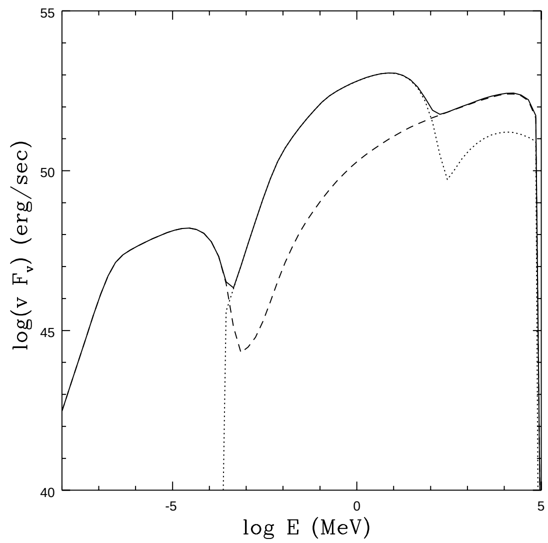

Figure 1: The model $\gamma-$ray spectrum of a GRB as seen in the frame of the observer: (a) The synchrotron component at energy $\varepsilon \sim 10^{-5}$ (b) The bulk Comptonized component at $E \simeq 2$ and (c) The inverse Compton component at energy Γ^2. All energies in units of the electron mass. The dashed lines are the Synchrotron and Inverse Compton components. The dotted line is the bulk Comptonized component and solid line the total emission. This extends to $\Gamma^2 m_e c^2$ even though no accelerated particles are present.

$p\gamma \rightarrow p e^+ e^-$ reaction. In addition to the bulk Comptonized component, the spectra also include a synchrotron component at $\varepsilon \sim 10^{-5} - 10^{-4}$ and an inverse Compton component at $E \simeq \Gamma^2$ (in units of $m_e c^2$), in broad agreement with the recent *Fermi LAT* observations.

2. Recent Developments

More recently, we have attempted to combine the evolution of the RBW with the production of radiation and the feedback of the radiation reaction force on its dynamics [5]. This integrated approach removes the arbitrariness of the conditions at the RBW and connects the conversion of the energy stored in relativistic protons on the RBW to the initial energy of the explosion and the distribution of matter in the circumburst medium. One should bear in mind that for the production of a GRB both the accumulated column of protons must be above the critical one *and* the LF must obey the kinematic threshold of Eq. (1.1). Starting with a RBW of $\Gamma \simeq 100$ propagating in a pre-supernova stellar wind medium, we were able to follow the combined production of radiation and its feedback on the EBW dynamics. In this specific case the initial LF of the RBW and the surrounding medium conditions were such that led to a short burst (duration $\Delta t \sim 0.2$); the radiation reaction slowed down the RBW at a radius close to the deceleration radius of the RBW, so that after a sharp decline in flux, the latter continued to decline but at a slower rate.

A different situation is depicted in Fig. (2), where the RBW evolution is followed from its point of origin, at $r = R_0$, to radii past its deceleration radius. Along the way, at $r \simeq 810^3 R_0$ it fulfills both the kinematic and dynamic thresholds; it releases its internal energy into radiation which forces its slowdown from $\Gamma \simeq 300$ to $\Gamma \simeq 130$. However, because the deceleration radius of

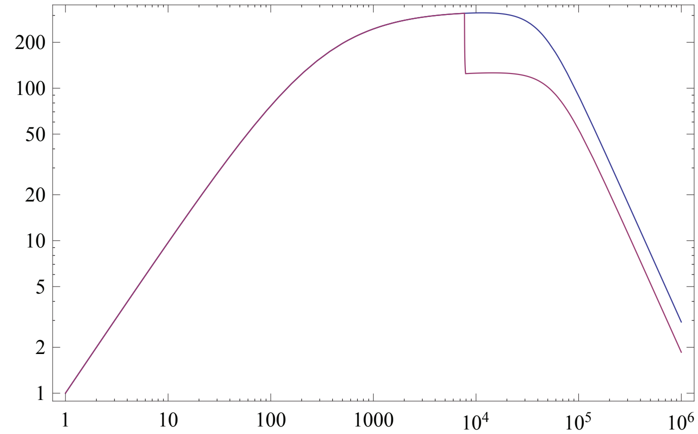

Figure 2: The evolution of the Lorentz factor of a RBW with radius in units of R_0. At $r \sim 10^4 R_0$, both threshold criteria are fulfilled; the energy release and bulk Comptonization of the radiation leads to decrease of Γ by a factor ~ 2. Γ remains at this value until the deceleration radius is reached and then follows the conventional decline. The blue and red lines depict the evolution with and without the effects of radiation reaction.

the RBW for these conditions (uniform density $n = 100$ cm^{-3}) is $R_d \simeq 10^5 R_0$, the RBW continues to propagate at $\Gamma \simeq 130$ until it reaches that radius. During this period the flux of the emitted radiation will remain constant and will commence its decline only after the RBW has gone past R_d. Such a behavior is consistent with that observed in a large number of XRT light curves [2] and has been considered one of the new puzzling features of GRBs revealed by the *Swift* observations. Within the “Supercritical Pile" model, this behavior is related to the effects of the process that produces the observed GRB $\gamma-$ray emission, namely photon bulk Comptonization.

One of the objections raised against this model has been that, because it involves primarily an external shock, it can only produce smoothly varying GRB, over time scales of order $\Delta t \sim R/c\Gamma^2 \simeq 300 R_{18} (300/\Gamma)^2$ sec, while there have been cases where individual subpulses of duration $\sim 10^{-2}$ sec. However, the postshock plasma, due to the Weibel instability, is likely to be not uniform but in the form of string-like structures with column much higher that the estimated average column. The result is a much decreased time of energy release and increased intensity. We hope to address this issue in more detail in the future.

References

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