PoS PROCEEDINGS OF SCIENCE

Afterglow emission in the context of an 'one-zone' radiation-acceleration model

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In the present work we focus on the interplay between stochastic acceleration of charged particles and radiation processes in a region of turbulent magnetized plasma, setting the framework for an 'one-zone' radiation-acceleration model for Gamma-Ray Burst (GRB) afterglows. Specifically, we assume that the particle distribution is isotropic in space and treat in detail the particle propagation in the momentum-space. The electron distibution is modified by the acceleration, synchrotron and Synchrotron Self-Compton (SSC) radiation and escape processes. The magnetic field as well as the particle injection rate are functions of time as measured in the comoving frame of the blast wave. In order to study the dynamical evolution of this system, we numerically solve the time-dependent Fokker-Planck equation for the electron distribution and present the obtained particle and photon spectra of an indicative example.

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1. Introduction

Based on the results of particle acceleration theory [6, 5] and simulations [2, 1], the majority of the works on the radiative signatures from GRB afterglows uses an already accelerated power-law particle distribution. A first effort to combine stochastic acceleration with adiabatic losses for particles in the GRB blast wave shell using the kinetic equation approach was made by [4]. Using the same approach, the present work aims to go one step further and combine the stochastic acceleration and radiation processes (synchrotron and SSC) into a time-dependent 'one-zone' model specified for the afterglow emission.

2. The model

We consider an adiabatic blast wave with initial energy E_0 and Lorentz factor Γ_0 that propagates into a constant density (n_0) external medium. We further assume a monoenergetic particle injection at $\gamma_{\rm inj} \approx \Gamma$ in the blast wave shell with comoving width $\Delta' = r/\Gamma(r)$. The total magnetic field consists of two components: (i) the non-turbulent one with strength $B(r) = (32\pi m_p n_0 \varepsilon_B c^2)^{1/2}\Gamma(r)$ and (ii) the turbulent one with a power spectrum in the wavenumber space given by $w(k)dk \propto k^{-q}dk$. The exponent q lies typically in the range $1-2$. Values less than unity, however, cannot be excluded from physical arguments. The interaction of particles with the MHD turbulence can be described in the 'quasi-linear' regime as a diffusion process in the particle momentum-space [7]. Moreover, synchrotron radiation and upscattering of the synchrotron emitted photons in the same region (SSC) act as energy loss processes. We treat particle escape from the acceleration/radiation region using an energy and time-dependent escape term, since the exact treatment of particle propagation inside the blast wave region is out of the scope of the present work. The equation that describes the time evolution of the particle distribution in the comoving frame is

$$\frac{\partial n}{\partial t'} + \frac{n}{t_{\rm esc}(\gamma,t')} = \frac{\partial}{\partial \gamma}\left[-\left(\dot{\gamma}_{\rm loss} + \frac{D(\gamma,t')}{\gamma}\right)n + D(\gamma,t')\frac{\partial n}{\partial \gamma}\right] + Q(\gamma,t'), \tag{2.1}$$

where $t' = \Delta'/c$ is the comoving (or dynamical) time and $n \equiv n(\gamma,t')$ is the number density of particles at comoving time t', having Lorentz factors between γ and $\gamma + d\gamma$. The diffusion coefficient is related to the acceleration timescale as $D(\gamma,t') = \gamma^2/2t_{\rm acc}(\gamma,t')$. The acceleration timescale can be modelled as $t_{\rm acc} = \tau_{\rm acc}(t')\gamma^{2-q}$. The particle escape is determined by the dynamical timescale of the problem, i.e. $t_{\rm esc} = At'\gamma^{q-2}$. Here A is a normalization constant chosen to ensure $t_{\rm esc} \geq t'$ for a certain range of Lorentz factors. The loss term in the right-hand side of eq. (2.1) is given by $\dot{\gamma}_{\rm loss} = -\frac{4\sigma_{\rm T}}{3m_e c^2}\left[u_{\rm B}(t') + u_{\rm syn}(\gamma,t')\right]\gamma^2$, where the synchrotron photon energy is calculated up to the frequency $\nu_{\rm up} = \max[\nu_{\rm s,max}, 3{\rm m_e c^2}/4{\rm h}\gamma]$. This accounts for the fact that mainly scatterings in the Thomson regime contribute to the energy losses. Finally, the last term in the right-hand side of eq. (2.1) is the particle injection rate given by $Q(\gamma,t') = \xi c\Gamma^2(r)n_0 r^{-1}\delta[\gamma - \Gamma(r)]$. Here ξ denotes the fraction of the kinetic energy that is used for particle acceleration and is treated as a free parameter. The remaining free parameters of the problem are: $E_0, \Gamma_0, n_0, \varepsilon_B, q$ and the exact functional form of $\tau_{\rm acc}(t')$.

3. Results

We numerically solve eq. (2.1) using an extension of the Chang-Cooper scheme [3]. For the blast wave dynamics we have assumed: $E_0 = 10^{53}$ erg/s, $\Gamma_0 = 100$ and $n_0 = 1$ part/cm^3. A redshift

$z = 0.1$ was used throughout the present work. We present the results for the case of turbulent exponent $q = 1/2$ which lies outside of the typical range of values. However, we have adopted this value because it results in a time-decreasing observed synchrotron peak frequency, at least in the deceleration phase of the blast wave. This is suggested by the following relations:

- if the acceleration is saturated due to particle escape: $\gamma_{\max} \propto t'^{1/3} \Rightarrow \nu^{\rm obs}_{\rm s,max} \propto t'^{-8/15}$
- if the acceleration is saturated due to synchrotron losses: $\gamma_{\max} \propto B^{-2/5} \Rightarrow \nu^{\rm obs}_{\rm s,max} \propto t'^{-18/25}$.

The explicit expressions for the acceleration and escape timescales used in this example are respectively: $t_{\rm acc} = 10^3 \left(\frac{\gamma}{10^3}\right)^{3/2}$ s and $t_{\rm esc} = 10^{9/2} t' \left(\frac{\gamma}{10^3}\right)^{-3/2}$ s. Finally, other parameters used are: $\varepsilon_B = 10^{-3}$ and $\xi = 2 \times 10^{-3}$. Panel (a) of Fig. 1 shows the evolution of the particle distribution. The quadratic dependence at the low-energy part and the exponential cutoff at high-energies is characteristic of the second order acceleration process. For intermediate Lorentz factors, the slope is found to be 0.5 (see the 4 first snapshots from top to bottom). At later times the two power-law segments merge into one (thick solid and dashed lines). Particles reach a stationary state with a distribution that resembles a relativistic Maxwellian. Note that the obtained slope 0.5 would be different for another value of q; the exact value depends also on the process that dominates in the particular energy range. The fact that particle escape from the emitting region becomes slower with increasing time results in hard particle spectra, i.e. spectra that peak at large Lorentz factors. This can also be seen in panel (b) of Fig. 1, where the time-evolution of the particle energy content is plotted. Note that the particle energy density decreases only slightly at late times. However, a more significant decrease of the energy content would be obtained in the case of time-increasing acceleration timescale.

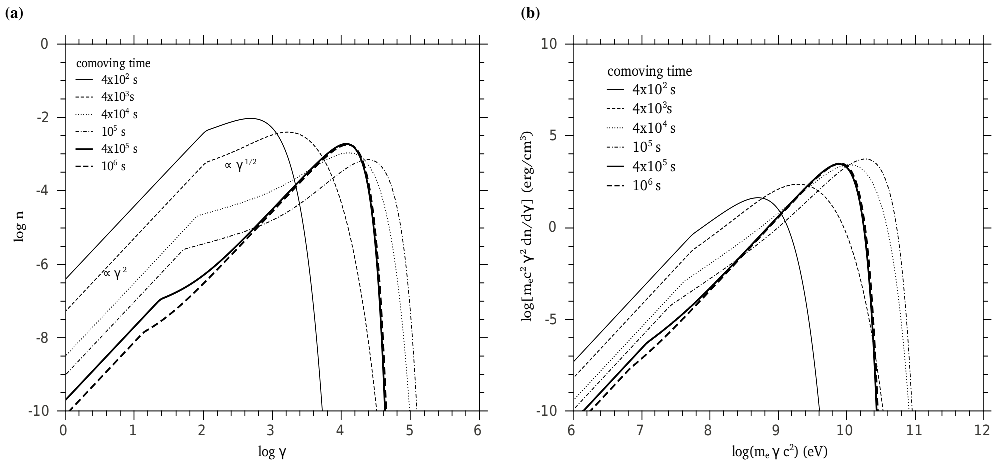

Figure 1: Snapshots of the particle distribution (panel a) and of the particle energy density (panel b). The system has reached a stationary state that is depicted with the thick solid and dashed lines in both panels.

The resulting observed photon spectra are shown in Fig. 2, where each snapshot is depicted with a different type of line. The corresponding time-instants are marked on the plot. Initially the spectrum is synchrotron dominated but at later times the SSC component becomes the dominant one. For $t' > 10^5$ s, i.e. soon after the beginning of the blast wave's deceleration phase, the synchrotron peak frequency decreases, as was mentioned earlier in this section. Note also that the spectral shape remains the same (apart from cutoff effects) during the whole evolution. For this set of parameters, a strong SSC emission in the γ-ray energy band is derived. Note however, that this can be avoided if one chooses, for example, a smaller ξ. Generally, the ratio of synchrotron to SSC peak fluxes is directly affected by ξ and ε_B. We have calculated also the light curves in five energy bands, starting from $10^{14} - 10^{15}$ Hz up to $10^{18} - 10^{19}$ Hz. The reason for this, is to show the variety of morphologies obtained. Radiation in higher energies emerges with a time-lag, which is typical of the acceleration process. Note also that spectral cutoff effects result in chromatic breaks (dash-dotted line). A direct comparison of the results shown in Fig. 2 with observations cannot or/and should not be made, since the latter requires an extensive search of the parameter space.

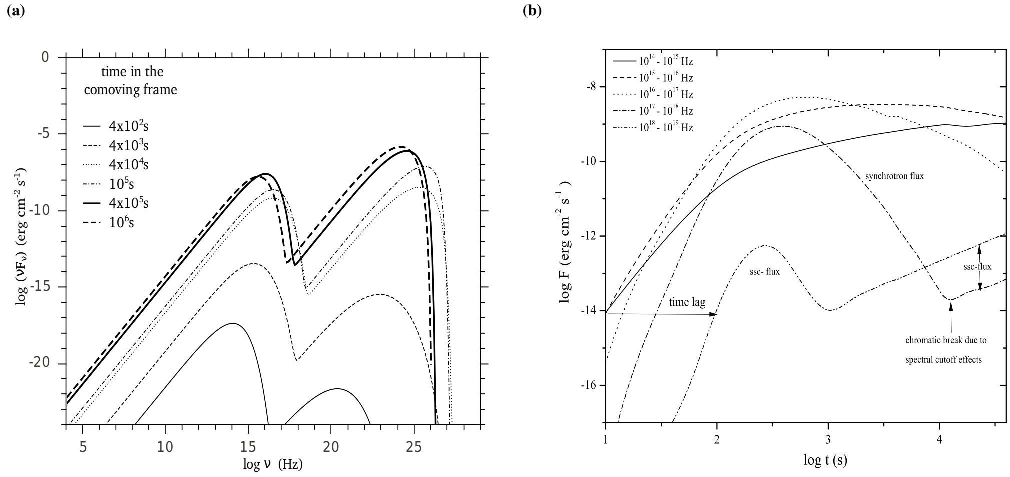

Figure 2: Snapshots of the observed photon spectra (in νF_ν units) are shown in panel (a). Light curves at indicative energy bands are shown in panel (b).

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