Microscopic Processes by RPIC Simulations

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Calculating Emission from Electrons in Self-consistently Generated Magnetic Fields

The electromagnetic instabilities mediating relativistic shocks generate magnetic fields and radiation is predicted to result from synchrotron emission of shock accelerated electrons. The observed spectrum of afterglow radiation is indeed remarkably consistent with synchrotron emission of electrons accelerated to a power-law distribution, providing support for the standard afterglow model. However, due to the lack of a first principles theory of collisionless shocks, a purely phenomenological approach to the model of afterglow radiation has been adopted without investigating in detail the processes responsible for particle acceleration and magnetic field generation. Therefore, the investigation of radiation resulting from accelerated particles (mainly electrons and positrons) in turbulent magnetic fields is essential to an understanding of the spectral properties of the radiation.

We have developed and implemented a numerical method to obtain spectra particles self-consistently traced in our PIC simulations. We calculate the radiation spectra directly from our simulations by integrating the expression for the retarded power, derived from Liénard-Wiechert potentials for a large number of representative particles in the PIC representation of the plasma. In order to obtain the spectrum of the synchrotron/jitter emission, we consider an ensemble of electrons selected in the region where the Weibel instability has fully grown and where the electrons are accelerated in the self-consistently generated magnetic fields.

We have validated our numerical method by performing simulations using a small system with $(L_{\rm x}, L_{\rm y}, L_{\rm z}) = (645\Delta, 131\Delta, 131\Delta)$ ($\Delta = 1$: grid cell size) and a total of ~ 0.5 billion particles (12 particles /cell/species for the ambient plasma) in the active grid cells. We first performed simulations without calculating radiation up to $t = 450\omega_{\rm pe}^{-1}$ when the jet front is located at about $x = 480\Delta$. We randomly selected 16,200 jet electrons near the jet front and calculated the emission during the sampling time $t_{\rm s} = t_2 - t_1 = 75\omega_{\rm pe}^{-1}$ with Nyquist frequency $\omega_{\rm N} = 1/2\Delta t = 200\omega_{\rm pe}$ where $\Delta t = 0.005\omega_{\rm pe}^{-1}$ is the simulation time step and the frequency resolution $\Delta\omega = 1/t_{\rm s} = 0.0133\omega_{\rm pe}$.

The spectra shown in Figure 1a are obtained for emission from electrons in jets with different Lorentz factors. We have simulated cold and warm electron jets with $\gamma = 10, 20, 50, 100, and 300$ and for a cold electron jet with $\gamma = 1000$ (Nishikawa et al. 2011e). Here the spectra are calculated for head-on radiation ($\theta = 0°$). It is noted that radiation loss is not included (Jaroschek et al. 2009; Medvedev & Spitkovsky 2009). The radiation from jet electrons shows a Bremsstrahlung-like spectrum at low frequencies for the eleven cases (Hededal 2005) because the magnetic fields generated by the Weibel instability are rather weak and jet electron acceleration is modest. While the lower frequencies have flat spectra and are Bremsstrahlung like, the higher frequency slopes in Fig. 1a are less steep than that in the Bremsstrahlung spectrum (Nishikawa et al. 2011a-e). This is due to the spread of accelerated electron Lorentz factors.

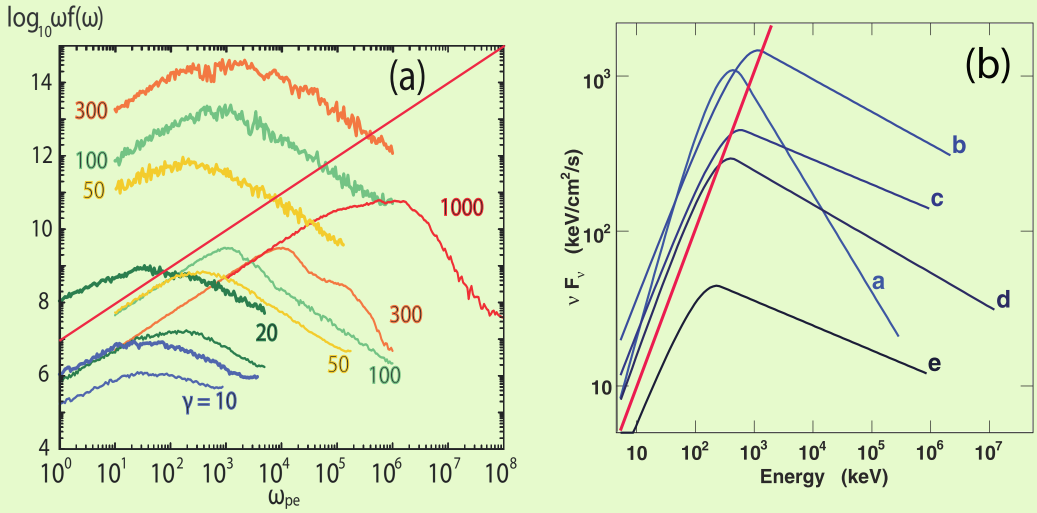

Fig. 1.— Comparison of synthetic spectra (Fig. 1a) and Fermi data (Fig. 1b) . Figure 1a shows the spectra for the cases of $\gamma = 10, 20, 50, 100, 300$ and 1000 with cold (thin lines) and warm (thick lines) electron jets. The low frequency slope is approximately 1 and is very similar to those of the spectra in Fig. 1b except interval "a". Figure 1b shows modeled Fermi spectra in νF_ν units for five time intervals based on Fermi data (Abdo et al. 2009). A flat spectrum would indicate equal energy per decade in photon energy. The changing shapes indicate the evolution of the spectrum over time.

The extension to higher frequencies is explained (see Fig. 7.16 (left) in Hededal's Ph. D. thesis; Hededal 2005) as a result of the turbulent magnetic fields in the emission region. We ran other simulations using different parameters for jet electrons and including ambient magnetic fields. However, the spectra for these cases proved very similar to the spectra shown in Figure 1.

Figure 1 shows how our synthetic spectra matched with spectra obtained from Fermi observations. Figure 1b shows the Fermi model spectra for five time intervals (Abdo et al. 2009). The solid red line indicates a slope of 1 and except for the interval "a" the slopes for all other time intervals are approximately 1. This is similar to a Bremsstrahlung-like spectrum at least for the low frequency side. As shown in Fig. 1a the synthetic spectral slopes at low frequencies are very similar to the Fermi observations. The spectral peaks and slopes at high frequencies change over time as shown in Fig. 1b. As expected, the spectral peaks for jet electrons with higher Lorentz factors are higher in frequency and amplitude. It should be noted that in simulations the spectra are normalized by the electron plasma frequency $\omega_{\rm pe}$ and, for example, $10^4\omega_{\rm pe}$ may correspond to 10^2 keV. Our simulation setup describes a relativistic jet propagating into an external medium as is appropriate to afterglows.