Simulation of relativistic shocks and associated radiation from turbulent magnetic fields

K.-I. Nishikawa*, J. Niemiec†, M. Medvedev**, B. Zhang‡, P. Hardee§, Å. Nordlund¶, J. Frederiksen¶, Y. Mizuno*, H. Sol‖, M. Pohl††, D. H. Hartmann‡‡ and G. J. Fishman§§

*National Space Science and Technology Center, Huntsville, AL 35805, USA
†Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, 31-342 Kraków, Poland
**Department of Physics and Astronomy, University of Kansas, KS 66045, USA
‡Department of Physics, University of Nevada, Las Vegas, NV 89154, USA
§Department of Physics and Astronomy, The University of Alabama, Tuscaloosa, AL 35487, USA
¶Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen Ø, Denmark
‖LUTH, Observatore de Paris-Meudon, 5 place Jules Jansen, 92195 Meudon Cedex, France
††Institut für Physik und Astronomie, Universität Potsdam, 14476 Potsdam-Golm, Germany, and DESY, Platanenallee 6, 15738 Zeuthen, Germany
‡‡Department of Physics and Astronomy, Clemson University, Clemson, SC 29634, USA
§§NASA/MSFC, Huntsville, AL 35805, USA

Abstract. Using our new 3-D relativistic particle-in-cell (PIC) code, we investigated long-term particle acceleration associated with a relativistic electron-positron jet propagating in an unmagnetized ambient electron-positron plasma. The simulations were performed using a much longer simulation system than our previous simulations in order to investigate the full nonlinear stage of the Weibel instability and its particle acceleration mechanism. Cold jet electrons are thermalized and ambient electrons are accelerated in the resulting shocks. Acceleration of ambient electrons leads to a maximum ambient electron density three times larger than the original value as predicted by hydrodynamic compression. Behind the bow shock, in the jet shock, strong electromagnetic fields are generated. These fields may lead to time dependent afterglow emission. In order to go beyond the standard synchrotron model used in astrophysical objects we have used PIC simulations and calculated radiation based on first principles. We calculated radiation from electrons propagating in a uniform parallel magnetic field to verify the technique. We also used the technique to calculate emission from electrons based on simulations with a small system. We obtain spectra which are consistent with those generated from electrons propagating in turbulent magnetic fields. This turbulent magnetic field is similar to the magnetic field generated at an early nonlinear stage of the Weibel instability. A fully developed shock within a larger system may generate a jitter/synchrotron spectrum.

Keywords: acceleration of particles, galaxies, jets, gamma rays bursts, magnetic fields, plasmas, shock waves, radiation
PACS: 98.62.Nx; 95.85.Pw; 95.85.Nv; 95.55.Ka; 52.27.Ny; 52.35.Qz; 52.35.Ra

INTRODUCTION

Particle-in-cell (PIC) simulations can shed light on the physical mechanism of particle acceleration that occurs in the complicated dynamics within relativistic shocks. Recent PIC simulations of relativistic electron-ion and electron-positron jets injected into an ambient plasma show that acceleration occurs within the downstream jet [**? ? ? ? ? ? ? ? ?**]. In general, these simulations have confirmed that relativistic jets excite the Weibel instability, which generates current filaments and associated magnetic fields [**?**], and accelerates electrons (for details, e.g., [**?**].

The general agreement between blast wave dynamics and direct measurements of the fireball size argue for the validity of this model for GRBs [**? ?**]. The shock is most likely collisionless, i.e., mediated by plasma instabilities [**?**]. The electromagnetic instabilities mediating the afterglow shock are expected to generate magnetic fields. Afterglow radiation was therefore 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 based on synchrotron emission of shock accelerated electrons [**? ? ? ? ? ? ? ?**].

A synchrotron shock model is widely adopted to describe the radiation thought to be responsible for observed broad-band GRB afterglows [**? ? ? ? ?**]. Associated with this model are three major assumptions that are adopted in almost all current GRB afterglow models. Firstly, electrons are assumed to be "Fermi" accelerated at the relativistic shocks and to have a power-law distribution with a power-law index p upon acceleration, i.e., $N(E_{\rm e})dE_{\rm e} \propto E^{-p}dE_{\rm e}$. This is consistent with recent PIC simulations of shock formation and particle acceleration [**?**] and also some Monte Carlo models [**? ? ?**], but see [**? ?**]. Secondly, a fraction $\varepsilon_{\rm e}$ (generally taken to be ≤ 1) of the electrons associated with ISM baryons are accelerated, and the total electron energy is a fraction $\xi_{\rm e}$ of the total internal energy in the shocked region. Thirdly, the strength of the magnetic fields in the shocked region is unknown, but its energy density $(B^2/8\pi)$ is assumed to be a fraction ε_B of the internal energy. These assumed "micro-physics" parameters, $p, \varepsilon_{\rm e}$ and $\varepsilon_{\rm B}$, whose values are obtained from spectral fits [**? ?**] reflect the lack of a detailed description of the microphysics [**?**].

Due to the lack of a first principles theory of collisionless shocks, a purely phenomenological approach to the model of afterglow radiation was ascribed without investigating in detail the processes responsible for particle acceleration and magnetic field generation [**?**]. It is important to clarify here that the constraints implied on these parameters by the observations are independent of any assumptions regarding the nature of the afterglow shock and the processes responsible for particle acceleration or magnetic field generation. Any model should satisfy these observational constraints.

The properties of synchrotron (or "jitter") emission from relativistic shocks will be determined by the magnetic field strength and structure and the electron energy distribution behind the shock. The characteristics of jitter radiation may be important to understanding the complex time evolution and/or spectral structure in gamma-ray bursts [**?**]. For example, jitter radiation has been proposed as a means to explain GRB spectra below the peak frequency that are harder than the "line of death" spectral index associated with synchrotron emission [**? ?**], i.e., the observed spectral power scales as $F_\nu \propto \nu^{2/3}$, whereas synchrotron spectra are $F_\nu \propto \nu^{1/3}$ or softer [**?**]. Thus, it is essential to calculate radiation production by tracing electrons (positrons) in self-consistently generated small-scale electromagnetic fields.

Therefore, the investigation of radiation resulting from accelerated particles (mainly electrons and positrons) in turbulent magnetic fields is essential for understanding radiation mechanisms and their observable spectral properties. In this report we present a new numerical method to obtain spectra from particles self-consistently traced in our PIC simulations.

CALCULATING EMISSION FROM ELECTRONS MOVING IN SELF-CONSISTENTLY GENERATED MAGNETIC FIELDS

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 size) and a total of ~ 0.5 billion particles (12 particles/cell/species for the ambient plasma) in the active grid zones [**?**]. 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 mass ratio is 1 ($m_{\rm e}/m_{\rm i} = 1$).

The spectra shown in Figure 1a are obtained for emission from jet electrons with $\gamma = 10, 20, 50, 100, 300$ and 1000. We have simulated cold (thin) and warm (thick) electron jets for the different Lorentz factors except the case of $\gamma = 1000$ (larger than the maximum value). Here the spectra are calculated for head-on radiation ($\theta = 0°$). It is noted that in this report the radiation loss is not included [e.g., **? ?**]. The radiation from jet electrons shows a Bremsstrahlung-like spectrum for the eleven cases [**?**]. Since the magnetic fields generated by the Weibel instability are rather weak and jet electron acceleration is modest, the electron trajectories bend only slightly.

Comparable to a Bremsstrahlung spectrum, the lower frequencies have flat spectra and the higher frequencies decrease [**?**]. However, the higher frequency slopes in Fig. 1a are less steep than that in the Bremsstrahlung spectrum. This is due to the fact that the spread of Lorentz factors of jet electrons is larger and the average Lorentz factor is larger as well. Furthermore, even when the magnetic field strength is not so large, the slope of the spectra seems to be extended to higher frequency. This is explained as shown in Fig. 7.16 (left) in Hededal's Ph. D. thesis [**?**] where the turbulent magnetic field shifts the frequency higher with shorter wave length (smaller μ). We ran simulations using several different parameters for jet electrons and ambient magnetic field using a small system as in this report. However, the strength of the magnetic fields generated by the Weibel instability is small, therefore the spectra for these

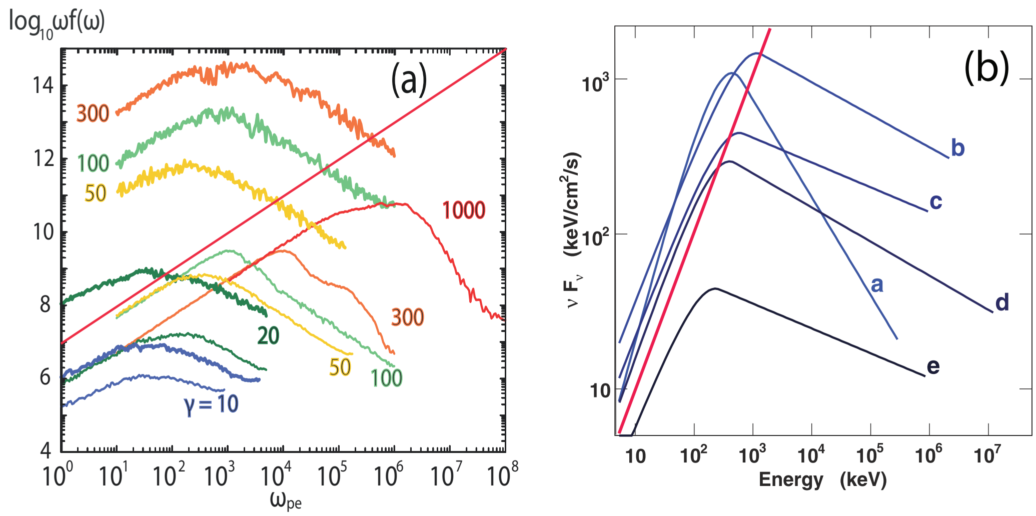

FIGURE 1. Brief comparison of synthetic spectra (Fig. 1a) and Fermi data (Fig. 1b) . Figure 1a shows the spectra for the cases of $\gamma = 10, 20, 50, 100, 300$ and 1000 with cold (thin lines) and warm (thick lines) electron jets. The low frequency slope is approximately 1 and is very similar to those of the spectra in Fig 1b except interval “a”. Figure 1b shows the model spectra in νF_ν units for five time intervals based on Fermi data [**?**]. A flat spectrum would indicate equal energy per decade in photon energy. The changing shapes show the evolution of the spectrum over time. The low frequency slope in Fig. 1a is approximately 1 which is very similar to those of the spectra in Fig 1b except interval “a”.

cases are very similar to the Bremsstrahlung spectrum.

Figure 1 shows how our synthetic spectrum matches with spectra obtained from Fermi observations. Figure 1b shows the model spectra for five time intervals [**?**]. The red line shows 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 observations. The 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 become higher in frequency and amplitude for cold jets (thin lines) as shown in Fig. 1a. The spectral peaks of warm jets (thick lines) are lower than those for cold jets, however the amplitudes become much higher. It should be noted that in simulations the spectra are normalized by the electron plasma frequency $\omega_{\rm pe}$ and considering various physical parameters, for example $10^4\omega_{\rm pe}$ may correspond to 10^2 keV. This simulation setup is for a relativistic jet into an external medium, which is appropriate for afterglows. However, we need to examine this issue further in order to compare synthetic with observed spectra.

DISCUSSION

Emission obtained with the method described above is obtained self-consistently, and automatically accounts for magnetic field structures on the small scales responsible for jitter emission. By performing such calculations for simulations with different parameters, we can investigate and compare the different regimes of jitter- and synchrotron-type emission [**? ?**]. Thus, we should be able to address the low frequency GRB spectral index violation of the synchrotron spectrum line of death [**?**].

Recently, synthetic radiation has been obtained from accelerated electrons in laser-wakefield acceleration [**?**], in counter-streaming jets [**?**], and in reflecting wall generated shocks [**?**]. In this report as in previous work [**?**], we inject relativistic jets into ambient plasma. A shock is formed and electrons are accelerated due to the Weibel instability and the shock. We calculate the radiation from jet electrons in the observer frame, therefore calculated spectra can be compared with observations directly.

Behind the trailing shock the electrons are accelerated and strong magnetic fields are generated [**?**]. Therefore, this region seems to produce the observed emission. We will examine the observed spectral changes over time using different plasma conditions such as jet Lorentz factors, jet thermal temperatures, and plasma composition.

ACKNOWLEDGMENTS

This work is supported by NSF-AST-0506719, AST-0506666, AST-0908040, AST-0908010, NASA-NNG05GK73G, NNX07AJ88G, NNX08AG83G, NNX 08AL39G, and NNX09AD16G. JN was supported by MNiSW research projects 1 P03D 003 29 and N N203 393034, and The Foundation for Polish Science through the HOMING program, which is supported through the EEA Financial Mechanism.Simulations were performed at the Columbia facility at the NASA Advanced Supercomputing (NAS). and IBM p690 (Copper) at the National Center for Supercomputing Applications (NCSA) which is supported by the NSF. Part of this work was done while K.-I. N. was visiting the Niels Bohr Institute. Support from the Danish Natural Science Research Council is gratefully acknowledged. This report was finalized during the program "Particle Acceleration in Astrophysical Plasmas" at the Kavli Institute for Theoretical Physics which is supported by the National Science Foundation under Grant No. PHY05-51164.

REFERENCES

. Abdo, A. A., et al. 2009, Science, 323, 1688
. Achterberg, A., Gallant, Y. A. Kirk, J. G., & Guthmann, A. X. 2001, MNRAS, 328, 393
. Bekefi, G., *Radiative Processes in Plasmas*, John Wiley & Sons, New York, 1966.
. Chang, P., Spitkovsky, A., & Arons, J. 2008, ApJ, 674, 378
. Ellison, D. C., & Double, G. P. 2002, Astroparticle Phys., 18, 213
. Frederiksen, J. T., Haugbølle, T., Medvedev, M. V., & Nordlund, Å. 2010, ApJ, 722, L114
. Hededal, C.B., Ph.D. thesis, Gamma-Ray Bursts, Collisionless Shocks and Synthetic Spectra, 2005. (arXiv:astro-ph/0506559)
. Hededal, C. B., & Nishikawa, K.-I. 2005, ApJ, 623, L89
. Jackson, J. D., *Classical Electrodynamics*, Interscience, 1999.
. Jaroschek C. H. & Hoshino, M. 2009, PRL, 103, 075002 1
. Landau, L. D., & Lifshitz, E. M.,*The Classical Theory of Fields*, Elsevier Science & Technology Books, 1980.
. Lemoine, M., & Pelletier, G. 2003, ApJ, 589, L73
. Martins, J.L., Martins, S.F., Fonseca, R.A. Silva, L.O., 2009, Proc. of SPIE, 7359, 73590V-1
. Medvedev, M. V., & Loeb, A. 1989, ApJ, 526, 697
. Medvedev, M. V. 2000, ApJ, 540, 704
. Medvedev, M. V. 2006, ApJ, 637, 869
. Medvedev, M.V., & Spitkovsky, A. 2009, ApJ, 700, 956
. Meszaros, P. 2002, ARAA, 40, 137
. Meszaros, P. 2006, Rept. Prog. Phys., 69, 2259
. Meszaros, P., & Rees, M. J. 1997, ApJ, 482, L29
. Nakar, E. 2007, Phys. Reports, 442, 166
. Niemiec, J., & Ostrowski, M. 2006, ApJ, 641, 984
. Niemiec, J., Ostrowski, M., Pohl, M. 2006, ApJ, 650, 1020
. Nishikawa, K.-I., Hardee, P., Richardson, G., Preece, R., Sol, H., & Fishman, G. J. 2003, ApJ, 595, 555
. Nishikawa, K.-I., Hardee, P., Richardson, G., Preece, R., Sol, H., & Fishman, G. J. 2005, ApJ, 623, 927
. Nishikawa, K.-I., Hardee, P., Hededal, C. B., & Fishman, G. J. 2006, ApJ, 642, 1267
. Nishikawa, K. -I., Niemiec, J., Sol, H., Medvedev, M., Zhang, B., et al. 2009, AIPCP, 1085, 589
. Nishikawa, K.-I., Niemiec, J., Hardee, P. E., Medvedev, M. et al. 2009, ApJ, 689, L10
. Nishikawa, K.-I., Niemiec, J., Medvedev, M., Zhang, B., Hardee, P., et al. 2011, Adv. of Space Res., 47, in press (arXiv:0906.5018v3)
. Panaitescu, A., & Kumar, P. 2001, ApJ, 560, L49
. Piran, T. 1999, Phys. Rep., 314, 575
. Piran, T. 2000, Phys. Rep., 333, 529
. Piran, T. 2005, Rev. Mod. Phys., 76, 1143
. Piran, T. 2005, AIPC, 784, 164
. Preece, R. D., Briggs, M. S., Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S. Band, D. L. 1998, ApJ, 506, L23
. Ramirez-Ruiz, E., Nishikawa, K.-I., & Hededal, C. B. 2007, ApJ, 671, 1877
. Rybicki, G. B., & Lightman, A. P., *Radiative Processes in Astrophysics*, John Wiley & Sons, New York, 1979.
. Sironi, L., & Spitkovsky, A. 2009, ApJ, 698, 1523
. Sironi, L. & Spitkovsky, A. 2009, ApJ, 707, L92
. Spitkovsky, A. 2008, ApJ, 673, L39
. Spitkovsky, A. 2008, ApJ, 682, L5
. Waxman, E. 2006, Plasma Phys. Control. Fusion, 48, B137
. Yost, S. A., Harrison, F. A., Sari, R., Frail, D. A. 2003, ApJ, 597, 459
. Zhang, B., & Meszaros, P. 2004, Int. J. Mod. Phys., A19, 2385
. Zhang, B., Gamma-Ray Bursts in the Swift Era, Chin. J. Astron. Astrophys., 7, 1 - 50, 2007