Electron acceleration in relativistic GRB shocks

BY MIKHAIL V. MEDVEDEV*

Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA

The shock model of gamma-ray bursts (GRBs) has two free parameters: $\epsilon_B$ and $\epsilon_e$. It has been shown that $\epsilon_B$ should range between few $\times 10^{-3}$ and few $\times 10^{-4}$. However, how to calculate the value of $\epsilon_e$ has remained an outstanding theoretical problem for over a decade. Here, we demonstrate that the Weibel theory inevitably predicts that $\epsilon_e \approx \sqrt{\epsilon_B}$. The GRB afterglow data fully agree with this theoretical prediction. Our result explains why the electrons are close to equipartition in GRBs. This $\epsilon_e - \epsilon_B$ relation can potentially be used to reduce the number of free parameters in afterglow models.

Keywords: gamma-ray bursts; particle acceleration; shock waves; magnetic fields

The problem of electron acceleration at GRB shocks has been an outstanding theoretical problem for over a decade. No theory, or even a working idea, existed until now that would allow us to calculate $\epsilon_e = U_e m_p c^2 n \Gamma$. The afterglow analyses has yielded the values clustered between a few per cent and a few tens percent. We use here the Weibel shock theory (Medvedev & Loeb 1999), which has been confirmed by three-dimensional PIC simulations up to time-scales of a few tens to a few hundred proton plasma times (Silva et al. 2003; Spitkovsky 2005; Medvedev et al. 2006). These simulations are thus representing internal shocks at distances of a few $\times 10^{13}$ cm and the (very) early afterglow phase, in which the electron cooling has a similar (i.e. few hundred plasma times or less) time-scale. The predictions of the theory are then extrapolated to the regime of the late afterglow. Comparison of the theoretical predictions with afterglow data (below) shows excellent agreement, which indicates that the Weibel shock theory is a viable model for all GRB shocks.

In baryon-dominated shocks, saturation occurs at the equipartition with the electrons, at the value $\epsilon_B \sim 10^{-3}$. At such low fields, protons keep streaming in current filaments, whereas the electrons, being much lighter than the protons, are quickly isotropized in the random fields and form a uniform background. The current filaments are formed by the protons moving roughly at the speed of light (their Lorentz factor is $\sim \Gamma$). Hence, they are sources of both the magnetic and the electrostatic fields (Hededal et al. 2004; Nishikawa et al. 2005). These fields are related to each other as $B = \beta E$, where $\beta = \sqrt{1 - \Gamma^{-1}} \sim 1$. An electron, moving towards a filament gains energy $u_e = eE l = eB l$. The typical radial distance the

*medvedev@ku.edu

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electron travels is about half the distance between the filaments, \( l \approx \lambda (c/\omega_{pp,rel}) \), where \( \lambda \) is the dimensionless parameter and \( c/\omega_{pp,rel} \) is the relativistic proton skin depth. The parameter \( \lambda \approx 1 \) accounts for the actual geometry of the filaments, the electrostatic shielding in plasmas, the effects of the electrons on the current distribution, etc. All these effects introduce only a small, factor of two, uncertainty. Finally, the electron energy density behind the shock front is \( U_e = n u_e = \lambda eBnc/\omega_{pp,rel} \). This equation can be cast into the form \( \epsilon_e = \lambda \sqrt{\epsilon_B} \).

To compare theory with observations, we have taken the most recent and the best analysed sample of data containing ten afterglows (Panaitescu 2005). These GRB afterglows were fitted to a number of afterglow models. For each model, the reduced \( \chi^2 \) was given and for models with ‘reasonably good fits’ (\( \chi^2/\text{d.f.} \leq 4 \)), the micro-physical parameters are given.

We plot \( \epsilon_e/\sqrt{\epsilon_B} \) for the best fit models in figure 1a. Clearly, the data are clustered around unity with only little scatter. This clustering is neither accidental, nor an artefact of fitting. To demonstrate this, we plot in figure 1b the values of \( \epsilon_e/\sqrt{\epsilon_B} \) for all models reported by Panaitescu (2005). The goodness of the fit for these models is \( \chi^2/\text{d.f.} \leq 4 \). The data points are scattered over almost three decades, which is consistent with degradation of statistical correlation of \( \epsilon_e \) and \( \epsilon_B \) in poor fits.

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References


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