Thermal electron production and consequences for GRB afterglows

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If you remember *one* thing...

\[ N(E) \]

\[ E_{\text{min}} \quad E_{\text{max}} \]

Energy

\[
\begin{align*}
E_{\text{min}} &< E < E_{\text{max}} \\
N(E) &\propto E^{-p}
\end{align*}
\]

Sironi et al. (2013)

Figure 11. Temporal evolution of the post-shock particle spectrum
Afterglow is long-lived (hours, days, months) multiwavelength relic of a gamma-ray burst (GRB)
Background

Observations of GRB afterglows cover orders of magnitude in time and energy

Perley et al. (2014) (2014ApJ...781...37P)

Figure 10. Observations of the afterglow of GRB 130427A spanning from the low-frequency radio to the 100 GeV LAT bands, interpolated to a series of coeval epochs spanning from 0.007 days (10 minutes) to 130 days after the burst. Overplotted over each epoch is our simple forward+reverse shock model from standard synchrotron afterglow theory, which provides an excellent description of the entire data set, a span of 18 orders of magnitude in frequency and 4 orders of magnitude in time. The solid line shows the combined model, with the pale solid line showing the reverse-shock and the pale dotted line showing the forward-shock contribution. The “spur” at $\approx 10^{15}$ Hz shows the effects of host-galaxy extinction on the NIR/optical/UV bands. Open points with error bars are measurements (adjusted to be coeval at each epoch time); pale filled points are model optical fluxes from the empirical fit in Section 3.4. The inset at lower left shows a magnified version of the radio part of the SED (gray box) at $t > 0.7$ days.
Many different models to explain broadband spectra and light curves

A complete reference of the analytical synchrotron external shock models of gamma-ray bursts

He Gao\textsuperscript{a}, Wei-Hua Lei\textsuperscript{b,a}, Yuan-Chuan Zou\textsuperscript{b}, Xue-Feng Wu\textsuperscript{c}, Bing Zhang\textsuperscript{a,d,e,*}
Many different models to explain broadband spectra and light curves

However, current afterglow studies assume extremely simple model for electrons accelerated by shock
The case for low-energy electrons

Works really well most of time, but sometimes runs into difficulty

Perley et al. (2014)
(2014ApJ...781...37P)

$0.007 \, \text{d}$

$130 \, \text{d}$
The case for low-energy electrons

Works really well most of time, but sometimes runs into difficulty

Furthermore, we find that the electrons and magnetic field are close to equipartition with $\epsilon_e \sim \epsilon_B \sim 0.5$.

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>MODEL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Forward Shock (ISM)</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>0.84$^{+0.06}_{-0.08}$</td>
</tr>
<tr>
<td>$\epsilon_B$</td>
<td>0.11$^{+0.07}_{-0.05}$</td>
</tr>
<tr>
<td>Forward Shock (wind)</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_e$</td>
<td>0.60</td>
</tr>
<tr>
<td>$\epsilon_B$</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Frail et al. (2000)  
(2000ApJ...537..191F)

Laskar et al. (2016)  
(2016ApJ...833...88L)
The case for low-energy electrons

Works *really* well most of time, but sometimes runs into difficulty

Laskar et al. (2014)
(2014ApJ...781....1L)
The case for low-energy electrons

All these numbers relied on radio observations.

Why is radio leading to suspicious results? Look at the model:

(Electrons assumed to form power law with index constant in time)

But, with shock acceleration,

- Have “non-nonthermal” particles: crossed shock but didn’t enter acceleration process
- Spectral index varies with Lorentz factor (will not be constant in time)
The case for low-energy electrons

Know this from particle-in-cell (PIC) simulations of relativistic low-magnetization shocks

Critical results:
• Plasma instabilities UpS from shock transfer energy from ions to electrons
• Electrons, ions both cross shock at $E \sim v_0 m_p c^2$
• Only small fraction (few %) enter shock accel process & become cosmic rays

Sironi et al. (2013) (2013ApJ...771...54S)
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"Low-energy": few to few tens of GeV

Figure 11. Temporal evolution of the post-shock particle spectrum

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(2013ApJ...771...54S)
The consequences of low-energy electrons

Use PIC results to guide Monte Carlo simulations of shock accel process in GRB afterglow

Why MC?
- PIC sims $\sim 10^9$ cm across, forward shock $>10^{13}$ cm. Too large space/time domain for computation
- MC approach balances versatility with simplicity: computable on desktop
The consequences of low-energy electrons

- Model shock acceleration process at select points in afterglow, then compute photon production
- Retain all shocked plasma, not just material currently interacting with shock

The consequences of low-energy electrons

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- Retain all shocked plasma, not just material currently interacting with shock.

- Consider 3 cases:
  - NT-only: ignore thermal population
  - TP (test particle): assume inefficient injection to shock accel process
  - NL (nonlinear): assume efficient injection, & all consequences

Note large populations at GeV energies!
The consequences of low-energy electrons

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- Photon processes treated:
  - Synchrotron
  - Inverse Compton
    - CMB
    - Synch. photons
    - ISRF
  - (p-p) π production
  - Absorption
    - SSA (at radio)
    - EBL (at GeV+)

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The consequences of low-energy electrons

- In X-ray & optical, all photons are synchrotron
- Just produced by different parts of electron distribution
- Huge (100x) difference in emission when thermal particles included
- Later, all three models similar since non-thermal tails almost identical
- How to distinguish TP and NL?


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The consequences of low-energy electrons

- How to distinguish TP and NL? Look at spectral index.
- Transition from thermal to non-thermal is smoother for NL model than for TP model.
- Thermal particles produce hard-soft-hard variation in spectral index.
- Height, width affected by efficiency of injection.

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The consequences of low-energy electrons
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• In radio band, thermal particles very important for both emission and absorption

• For same GRB parameters, huge boost (100x) in radio emission with no change in optical, X-ray

• Fitted GRB parameters will be very different if thermal particles included
The consequences of low-energy electrons

- Presence of hot thermal particles robustly required by plasma physics

\[ \varepsilon_e \approx \lambda \varepsilon_B. \]

Note that we made no assumptions about compression and that the pressure is already occurring (which we are). We only used the fact that these particles are due to proton currents, which generate electrostatic fields. These electrostatic fields locally

Consequently, their momentum dispersion amounts to \( \Delta p_u^2 \sim m_p^2 c^2/2 \) once the electrons reach the shock front, which corresponds to equipartition with the incoming ions.

\[ B_z / \sqrt{4\pi \Gamma n_0 m_e c^2} \]

\( \sigma = 0 \)

\[ x - x_{sh} \] [c/\( \omega_{pe} \)]

\[ y \] [c/\( \omega_{pe} \)]

\[ x \cdot (c/\omega_{pe}) \]

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- Thermal particles have large impact on photon production & absorption processes

- Expect “standard model” for afterglow to change dramatically
The future of low-energy electrons

• Problem: can’t precisely predict yet how standard afterglow model will change

• Many additional steps needed
  ➢ Energy transfer at late times
  ➢ Physically-motivated magnetic field structure
  ➢ Analytical approximations
  ➢ Spanning GRB-environment parameter space
  ➢ (Neutrinos & multimessenger astronomy?)
  ➢ (Heavy nuclei?)
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• With no plasma instabilities, no energy transfer

• With no energy transfer, thermal electrons too cold to radiate significantly

• Key filamentation instability quenches around $\gamma_0 = 10$

• What happens after? Nobody knows

$Lemoine & Pelletier (2011) (2011MNRAS.418L..64L)$

Sironi et al. (2013) (2013ApJ...771...54S)

\[ \gamma_{sh} \gg \xi_b^{-1/3} \left( \frac{m_e}{m_p} \right)^{-1/3} \left( \frac{k_\perp c}{\omega_p} \right)^{1/3} \left( \frac{\omega_p}{\gamma_b} \ll k_\perp c \ll \omega_p \right). \]

One can thus check that, indeed, for $\gamma_{sh} = 10$ (corresponding to $\gamma_b \approx 100$), the above condition is violated.
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- What happens after? Nobody knows

- Need PIC simulations to determine behavior of instability, but have to beg others to do them for me

\[
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Conclusions

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