Astron. Astrophys. Suppl. Ser. **138**, 549–550 (1999)

Particle acceleration at ultra-relativistic shocks

Gamma-ray burst afterglow spectra and UHECRs

Y.A. Gallant[1], A. Achterberg[1], and J.G. Kirk[2]

[1] Astronomical Institute, Utrecht University, P.O. Box 80 000, 3508 TA Utrecht, Netherlands
[2] Max–Planck–Institut für Kernphysik, Postfach 10 39 80, 69029 Heidelberg, Germany

Received December 18, 1998; accepted January 26, 1999

Abstract. We consider particle acceleration of the Fermi type at the ultra-relativistic shock bounding an expanding relativistic fireball. We distinguish between the initial shock crossing cycle, in which particles can gain a large factor in energy, and subsequent crossing cycles, where the energy typically only doubles. We show that repeated shock crossings yield a power-law spectrum of accelerated particles with index $p \sim 2.2 - 2.3$, compatible with afterglow observations. We suggest that ultra-high-energy cosmic rays (UHECRs) might be produced by the initial boost in a relativistic fireball expanding into a pulsar wind bubble created by the progenitor system.

Key words: acceleration of particles — relativity — shock waves — gamma-rays: bursts — cosmic rays

1. Particle acceleration at relativistic blast waves

The relativistic fireball model assumes that the event which gives rise to a gamma-ray burst (GRB) deposits an energy $\mathcal{E}$ into a small baryonic mass M, such that $\eta \equiv \mathcal{E}/(Mc^2) \gg 1$. Typically η is assumed to be of order 10^2 to 10^3. After an initial acceleration phase, such a fireball reaches a "coasting" stage with Lorentz factor $\Gamma \sim \eta$. The fireball drives a blast wave of Lorentz factor $\Gamma_{\rm sh} \approx \sqrt{2}\,\Gamma$ into the surrounding medium. The energy expended to shock the surrounding medium eventually decelerates the fireball; in the adiabatic case, the Lorentz factor of the blast wave then decreases with radius as $\Gamma_{\rm sh} \propto R_{\rm sh}^{-3/2}$ (Rees & Mészáros 1992).

While the GRB emission itself may come from internal shocks (Rees & Mészáros 1994), the afterglow emission is generally thought to be due to electrons accelerated by the blast wave in its deceleration phase (e.g. Mészáros & Rees 1997; Vietri 1997). Fireball models of GRB afterglows (e.g. Sari et al. 1998) usually assume that these accelerated electrons have a power-law spectrum of unspecified index p. Waxman (1995) and Vietri (1995) also suggested that ultra-high-energy cosmic rays (UHECRs), with energies $E \gtrsim 10^{18.5}$ eV, might be accelerated in these relativistic fireballs. In particular, Vietri (1995) argued that in Fermi-type acceleration at an ultra-relativistic shock, a particle could have an energy gain $E_{\rm f}/E_{\rm i} \sim \Gamma_{\rm sh}^2$ per shock crossing cycle.

Motivated by these considerations, we examine acceleration of the Fermi type at an ultra-relativistic shock in more detail, considering first the spectral index of the accelerated particles, and then the maximum energy attainable by this process.

2. Energy gain per shock crossing cycle

The essential assumption of Fermi-type shock acceleration is that particles are deflected elastically in the local fluid frame on either side of the shock, so that upon recrossing upstream after an excursion downstream, say, they will have a net average energy gain. For particles of Lorentz factor $\gamma \gg \Gamma_{\rm sh} \gg 1$, this energy gain can be expressed as

$$\frac{E_{\rm f}}{E_{\rm i}} = \Gamma_{\rm rel}^2\,(1-\beta_{\rm rel}\cos\theta_{\rm i})\,(1+\beta_{\rm rel}\cos\theta'_{\rm f})\,, \quad (1)$$

where $\Gamma_{\rm rel} \approx \Gamma_{\rm sh}/\sqrt{2}$ is the relative Lorentz factor of the upstream and downstream media, θ is the angle between the particle's velocity at shock crossing and the shock normal, and primed and unprimed quantities are respectively measured in the downstream and upstream frames.

Kinematics require that the second factor in parentheses in Eq. (1) be greater than 1. In the initial shock crossing, $\theta_{\rm i}$ is isotropically distributed, and we do find $E_{\rm f}/E_{\rm i} \sim \Gamma_{\rm rel}^2$. For physically realistic deflection processes upstream, however, it can be shown that for all subsequent shock crossings, $\theta_{\rm i} \sim \Gamma_{\rm sh}^{-1}$, so that we typically have $E_{\rm f}/E_{\rm i} \sim 2$ (Gallant & Achterberg 1998, 1999).

Send offprint requests to: Y.A. Gallant

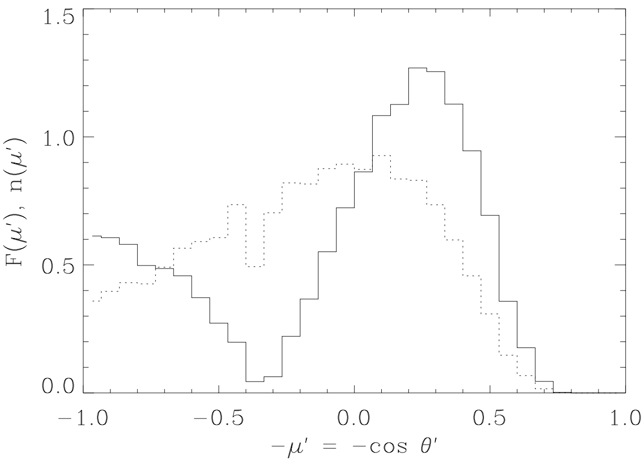

Fig. 1. Asymptotic angular distribution of the particles at shock crossing in the case of direction-angle scattering upstream, expressed both in terms of flux $F(\mu')$ (solid line) and density $n(\mu')$ (dashed line), each normalised to unity

3. Spectrum of Fermi-accelerated particles

The average energy gain, and hence the spectrum of accelerated particles, depends on the distribution of shock crossing angles θ. This distribution, which will be highly anisotropic in the case of an ultra-relativistic shock, depends in turn on the assumed deflection mechanism, and may be obtained by numerical simulation (Bednarz & Ostrowski 1998; Gallant et al. 1998).

Figure 1 shows the distribution obtained by Gallant et al. (1998) for the case of scattering in random magnetic fields both upstream and downstream, which yielded a spectral index $p \sim 2.25$. The case of regular deflection by a large-scale field upstream yielded an only slightly different index $p \sim 2.3$. Bednarz & Ostrowski (1998), for various levels of scattering parallel and perpendicular to the average magnetic field direction, found an asymptotic value of $p \sim 2.2$ for sufficiently relativistic shocks.

It is noteworthy that the values of p obtained in these simulations are compatible with those inferred from observations of the afterglows of GRB 970228, GRB 970402 (Waxman 1997) and GRB 970508 (Galama et al. 1998).

4. Maximum energy of accelerated particles

The energy attainable by Fermi acceleration at the external shock is limited by the requirement that the time to deflect the particle upstream must be shorter than the age of the fireball. This yields a maximum value

$$E \lesssim 5\ 10^{15}\, Z\, B_{-6}\, \eta_3^{1/3} \mathcal{E}_{52}^{1/3} n_0^{-1/3}\ \mathrm{eV}, \tag{2}$$

where Z is the particle's charge, $\mathcal{E} \equiv \mathcal{E}_{52}\, 10^{52}$erg is the fireball energy, and $B \equiv B_{-6}\, 10^{-6}\,\mathrm{G}$ and $n \equiv n_0\,\mathrm{cm}^{-3}$ are the surrounding medium magnetic field and density (Gallant & Achterberg 1998, 1999). For electrons, the deflection time must also be shorter than the radiative loss time, but the age limitation turns out to be more restrictive.

Given Galactic magnetic fields, Eq. (2) rules out the acceleration of UHECRs by repeated shock crossings at the external blast waves of GRB fireballs. Nonetheless, the initial boost by a factor $\sim \Gamma_{\mathrm{sh}}^2$ could yield UHECRs if there were relativistic particles of sufficient energy upstream, as it requires only the time for these particles to be deflected *downstream*, where the magnetic field could be amplified by turbulence. If the seed relativistic particles are cosmic rays typical of the Galactic ISM, however, this process is much too inefficient to account for the observed UHECRs.

Gallant & Achterberg (1998, 1999) instead proposed that in the context of the neutron star binary merger scenario for GRBs (e.g. Narayan et al. 1992), the fireball expands into a pulsar wind bubble blown in the ISM by the progenitor system. Because the energy density of the surrounding medium is then predominantly in the form of relativistic particles, these can be boosted by the blast wave with very high efficiency.

Gallant & Achterberg (1999) also showed that for parameters typical of the millisecond pulsars in the neutron star binaries observed in our Galaxy, the GRB blast wave would decelerate within the pulsar wind bubble, yielding a spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-2}$ for the boosted particles. Moreover, this spectrum would typically extend over the energy region $10^{18.5}\,\mathrm{eV} \lesssim E \lesssim 10^{20}\,\mathrm{eV}$, which is precisely where the UHECR component is observed.

Acknowledgements. This work was supported by ASTRON project 781–71–050 and by the European Commission under TMR programme contract FMRX–CT98–0168.

References

Bednarz J., Ostrowski M., 1998, Phys. Rev. Lett. 80, 3911
Galama T.J., et al., 1998, ApJ 500, L101
Gallant Y.A., Achterberg A., 1998, in: Rayos Cósmicos 98, Medina J. (ed.), Proc. 16th European Cosmic Ray Symposium, Alcalá de Henares (Madrid), p. 253
Gallant Y.A., Achterberg A., 1999, MNRAS 305, L6
Gallant Y.A., Achterberg A., Kirk J.G., 1998, in: Rayos Cósmicos 98, Medina J. (ed.), Proc. 16th European Cosmic Ray Symposium, Alcalá de Henares (Madrid), p. 371
Mészáros P., Rees M.J., 1997, ApJ 476, 232
Narayan R., Paczyński B., Piran T., 1992, ApJ 395, L83
Rees M.J., Mészáros P., 1992, MNRAS 258, 41P
Rees M.J., Mészáros P., 1994, ApJ 430, L93
Sari R., Piran T., Narayan R., 1998, ApJ 497, L17
Vietri M., 1995, ApJ 453, 883
Vietri M., 1997, ApJ 478, L9
Waxman E., 1995, Phys. Rev. Lett. 75, 386
Waxman E., 1997, ApJ 485, L5