GRB 輻射機構

~PHOTOMESON PROCESSES IN GAMMA-RAY BURSTS~

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1 Introduction

Since the origin of the GRB energy is the dissipation of the kinetic energy, protons may carry a much larger amount of energy than electrons initially. In the standard GRB model, it has been considered that a large fraction of protons' energy in the shocked region is transfered to electrons, and the synchrotron radiation is emitted by the relativistic electrons. However, the standard model has many problems to solve. For example, the clustering of the break energies is one of them. The synchrotron model cannot well explain the low-energy power-law index of GRB spectra. The point we notice in this paper is that the Coulomb interaction cannot transport protons' energy into electrons to achieve energy equipartition (Totani 1999). The time scale of the Coulomb interaction is much longer than the dynamical timescale.

In this paper, we consider the case that protons' energy in the shocked region cannot be efficiently transfered to electrons that primarily exist, and the emission from the electrons is negligible. We notice the Fermi accelerated protons that may have a large fraction of the internal energy. The physical conditions in GRBs imply that protons may be Fermi accelerated to high energies. Assuming the accelerated protons have a large fraction of the internal energy, we discuss the emission from the particles produced from the high energy protons.

2 Residue of the Radiation Field in the Fireball

The internal shock model can be described by collisional shells accelerated by the fireballs. In the radiation-dominated phase, the radiation energy density in the fireball behaves as $e \propto r^{-4}$, and the Lorentz factor γ of the fireball increases in proportion to r (Piran, Shemi & Narayan 1993). In the matter-dominated regime the radiation energy density declines as $e \propto r^{-8/3}$ and the shell coasts with $\gamma = \eta \equiv E/Mc^2$, where M and E are the baryon rest mass and total energy of the fireball, respectively. The fireball becomes optically thin at the Thomson photosphere $R_{\rm ph} = \sqrt{(\sigma_{\rm T} M)/(4\pi m_{\rm p})}$, where $\sigma_{\rm T}$ is the Thomson cross section. The photosphere becomes 6×10^{12}-6×10^{13} cm for the range $Mc^2 = 10^{48}$-10^{50} ergs. The radius of the photosphere is comparable to the typical radius where the internal shocks occur. The initial volume of the fireball is expressed as Δ^3 where Δ is the shell width in the observer frame. Then we obtain the temperature of the residual radiation field at the photosphere as

$$T = 130(\eta_3 \Delta_7 M_{48})^{-1/12} \quad \text{eV}, \tag{1}$$

where $\eta_3 = \eta/10^3$, $\Delta_7 = \Delta/10^7$ cm, and $M_{48} = Mc^2/10^{48}$ ergs. The parameter dependence of the temperature is very weak. The shell coasts $R_{\rm esc} \equiv 2\eta^2\Delta \sim 2 \times 10^{13} \Delta_7 \eta_3^2$ cm from the photosphere before the photon field escapes from the shell. Since the collision radius is comparable to $R_{\rm esc}$ for the rapid shell with $\eta \sim 10^3$, internal shocks can occur in the thermal radiation field with temperature ~ 100 eV.

Since the radiation field in the slower shell escapes immediately, we discuss only the reverse shocked region in the fluid's rest frame below. Internal shocks are mildly relativistic. We suppose the Lorentz factor $\gamma_{\rm R}$ of the reverse shock observed from the rapid shell's rest frame is about 2-3. From the jump condition, the shell width in the comoving frame is $l = \Delta\gamma_r/(4\gamma_{\rm R} + 3) \sim 10^9 \Delta_7 \eta_3$ cm. Hereafter we assume the internal shocks occur around the photosphere.

Then the internal energy density in the shocked shell is obtained as $U = (\gamma_R - 1)(4\gamma_R + 3)m_pc^2/(\sigma_T\eta\Delta)$. As conventionally assumed, if the constant ratio f_B of the internal energy U goes into the magnetic field, we obtain the magentic field at the photosphere as $B = \sqrt{8\pi f_B U}$. If we assume $(\gamma_R - 1)(4\gamma_R + 3) \sim 10$, $B \sim 2 \times 10^6 \Delta_7^{-1/2}\eta_3^{-1/2}$ G for $f_B = 0.1$.

The power-law distributed protons may have a large fraction of the internal energy. The thermal photons interact with these protons and produce photopions. The Lorentz factor of the typical protons that interact with the thermal photons is $\gamma_{p,typ} = \varepsilon_{th}/T$, where $\varepsilon_{th} \sim 145$ MeV is the threshold energy of the photon in the proton rest frame. The typical energy of protons becomes $E_{p,typ} \sim 10^{15}$ eV for $T = 100$ eV. We approximate the photopion production cross section (e.g. Stecker 1968) by a broken power-law profile. Then the optical depth of protons is $\sim 8(l/10^9\mathrm{cm})$ for $E_p = E_{p,typ} \sim 10^{15}$ eV. Therefore almost all the protons of 10^{15}-10^{16} eV produce π^0s and $\pi^{\pm}$s.

Since the inelasticity is about 20%, the typical energy of pions should be 10^{14}-10^{15} eV. The created π^0s decay immediately into gamma-rays. On the other hand, the life time of $\pi^{\pm}$s (~ 0.2 sec for 10^{15} eV) is longer than the dynamical time scale $l/c \sim 0.03$ sec because of the large Lorentz factor. Assuming the magnetic field $B \sim 10^6$ G, the cooling time ($\sim 2 \times 10^{-3}$ sec for 10^{15} eV) is short enough. Pions of 10^{14}-10^{15} eV emit photons of 10^7-10^9 eV.

These high energy photons emitted from π^0s or $\pi^{\pm}$s create electron-positron pairs. For $l = 10^9$ cm, the photons from $\varepsilon_\tau = 3 \times 10^8$ eV to 4×10^{14} eV create electron-positron pairs. The optical depth is larger than one in this energy range. Reiterating the pair creation and the synchrotron radiation, these high energy photons cascade into the low energy pairs. As electron-positron pairs cascade, the number density of pairs roughly distribute as $n_{\pm} \propto \gamma_{\pm}^{-3}$. The threshold energy ε_τ for the pair-creation should roughly correspond to the typical energy of electron-positron pairs. The typical energy of the synchrotron emission is $\varepsilon_{\pm} \sim 4(B/10^6\mathrm{G})$ keV. These typical photons will be blueshifted by the relativistic motion of the shocked shell ($\gamma_m \sim 100$) and observed as few hundreds keV.

3 Emission from Cascading Particles

As was discussed in section 2, the residue of the radiation field in the fireball can be a trigger of the emission from the cascading particles. The photon field due to the cascading particles itself will overwhelm the thermal radiation field later. The physical condition of the cascading particles may be derived from the photon field emitted from the particles themselves. In this case ε_τ we mentioned in the last section is not the typical energy of particles. For simplicity, we assume that the ratio f_γ of the internal energy U in the shocked shell goes into the radiation field, and the photon number density obeys the power-law distribution as $n(\varepsilon_\gamma) = (\alpha - 2)(f_\gamma U)/(\varepsilon_0^2)(\varepsilon_\gamma/\varepsilon_0)^{-\alpha}$ for $\varepsilon_\gamma \geq \varepsilon_0$. Of course, this will not be generally consistent with the radiation field that will be finally derived. As will be shown below, however, the typical energy of the cascading particles is not much sensitive to the shape of the spectrum. The typical energy of the cascading particles is depend on mainly f_γ. In this photon field, the optical depth for the photopion process is analytically obtained as $\tau_\pi(\gamma_p) \propto f_\gamma \varepsilon_0^{\alpha-2}\gamma_p^{\alpha-1}$. We define $\gamma_{p,\tau}$ as $\tau_\pi(\gamma_{p,\tau}) = 1$. Since $\gamma_{p,\tau} \propto f_\gamma^{1/(\alpha-1)}\varepsilon_0^{(2-\alpha)/(\alpha-1)}$, the threshold Lorentz factor $\gamma_{p,\tau}$ is almost independent of ε_0, if $\alpha \sim 2$. If $\alpha = 2.2$ and $\varepsilon_0 = 1$ keV, all protons, whose energy is larger than $\gamma_{p,\tau}m_pc^2 = 10^{13}(f_\gamma/0.3)^{-5/6}$ eV, produce photopions. The total cross sections of $\gamma + p$ and $\gamma + n$ reactions are almost equal. Since the inelasticity is about 0.2, all energy of protons $\geq 5 \times 10^{13}$ eV goes to photopions.

The produced π^0s decay into gamma-rays. As is tha cese in the thermal photon field, the photons in the power-law photon field cascade into the low energy pairs. The opotical depth for the pair creation is analytically obtained as $\tau_{\gamma\gamma} \propto f_\gamma \varepsilon_\gamma^{\alpha-1}\varepsilon_0^{\alpha-2}$ by a similar way of the case for the photopion process. If $f_\gamma \sim 0.3$, photons with energy ≥ 1 MeV cannot escape from the shell because of the large optical depth for the pair creation. Reiterating the pair creation and the synchrotron radiation, the fast cooling in the steady state makes the electron-positron pairs distribute as $n_\pm \propto \gamma_\pm^{-3}$. The created pairs above ~ 1 MeV may distribute in a monotonic fashion. Since there is no reason for making a discontinuity in the distribution of the electron-positron pairs above 1 MeV, only the self absorption frequency corrsponds to a break of the spectrum. It is very difficult that the self-absorption frequency reaches the X-ray band.

However we can expect that the charged pions have larger energy fraction than the neutral pions. Muons cool down through the synchrotron and inverse Compton mechanisms. The muons, whose energy is smaller than $10^{12}(l/10^9\mathrm{cm})^{1/2}((f_\gamma + f_\mathrm{B})/0.4)^{-1/2}$ eV, should decay into electrons before they cool down. Almost all muons lose their energy before decaying. The cooling time is $t_{\mu,\mathrm{cool}} \sim 0.03(l/10^9\mathrm{cm})^{1/2}((f_\gamma + f_\mathrm{B})/0.4)^{-1/2}$ sec that is comparable to the dynamical time scale l/c. The typical energy of muons' synchrotron radiation is ~ 20 keV for $l = 10^9$ cm, $f_\gamma = 0.3$, and $f_\mathrm{B} = 0.1$. This energy should be blueshifted by the relativistic motion of the shocked shell ($\gamma_m \sim 100$) and observed as $\sim$ MeV. We cannot observe emission from the cooled muons. This is favorable for the observed sharp break and low-energy power-law index of GRB spectra.

4 Conclusions

The purpose of our attempt is to examine whether the fireball model can reproduce GRBs without the energy transfer from protons to the primal electrons. The Fermi accelerated protons with $\geq 10^{13}$ eV bring their energy into pions. If protons of number fraction ζ are accelerated and distributed as $n_\mathrm{p} \propto E_\mathrm{p}^{-p}$ and have the energy of the fraction ξ of the internal energy, the energy fraction of pions is obtained by

$$f_\pi \sim \left(\frac{p-2}{p-1}\right)^{p-2} \zeta^{2-p}\xi^{p-1}\left(\frac{E_\mathrm{p,typ}}{m_\mathrm{p}c^2}\right)^{2-p} \tag{2}$$

$$= 0.3\left(\frac{\zeta}{0.01\%}\right)^{-0.2}\left(\frac{\xi}{50\%}\right)^{1.2}\left(\frac{E_\mathrm{p,typ}}{10^{13}\mathrm{eV}}\right)^{-0.2}, \tag{3}$$

for $p = 2.2$. The particles cascaded from the pions emit photons in a wide energy range. The muons can emit gamma-rays by the synchrotron and reproduce the sharp break in the spectrum. However, a significant amount of radiation due to the electron-positron pairs contaminates the spectrum. The emission from the pairs has no sharp break in the range of gamma-ray band.

The radiation due to the photopion production may occur, even if the energy transfer from protons to the primal electrons is admitted by unknown processes. If an internal shock occurs at a smaller radius, the efficiency of the photopion production becomes higher and the flux due to the cascading particles can be considerable in comparison with those emitted from the primal electrons. The contribution of the cascading particles may produce an anomalous spectrum like the "X-ray rich GRB" or GRB precursor.

References

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