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Radiation from Internal Shocks in Magnetized Flows

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Abstract: We consider the internal shock formation in magnetized outflows and we examine the plastic collision between such relativistic shells taking into account a possible dissipation of magnetic energy. We find that after the collision a large percentage of energy is released in thermal form and consequently we assume that this is transferred into protons which obtain a relativistic Maxwellian distribution. The relativistic thermal proton plasma is dense enough to suffer substantial energy losses through proton-proton interactions and thus to transfer its initial energy into photons, electron-positron pairs and neutrinos. We estimate the radiated photon and neutrino spectra by following the evolution of protons, electrons and photons as they interact with each other and with the magnetic field as well.

Introduction

Internal shocks that are formed when different shells of an outflow moving with different velocities collide with each other, are one of the plausible explanations of the GRB prompt emission [1, 2, 3], based on the outflow energy being partly thermalized and subsequently radiated. However, several aspects of the scenario remain unclear. One of the problems is the low shock efficiency (in thermalizing the outflow energy); another is the transfer of the thermalized energy into radiation and the formation of the prompt emission spectrum.

The present paper gives possible answers to these two problems. First we examine how the electromagnetic field of a magnetized flow could increase the amount of thermalized energy – through dissipation – making the shock efficiency higher than in a purely hydrodynamic flow. Second we investigate the hadronic cascade that ensues when the thermalized protons start interacting with each other and convert their energy into radiation and neutrinos within a very short time interval.

Internal shock formation

In a rather simple formulation we consider the inhomogeneous outflow as a collection of discrete

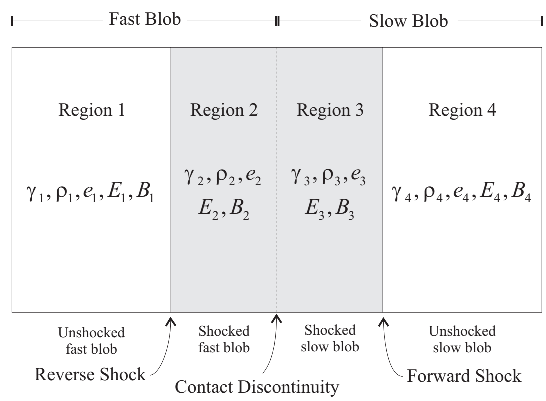

Figure 1: The geometry of the collision and the regions that are formed (ρ, e, E, B are the density, energy density, electric, and magnetic field, respectively, for each region).

shells moving with different Lorentz factors γ_i, so faster portions of ejecta can catch up slower ones and collide. We use the semi-analytical magnetohydrodynamical model of [4, 5] to describe the motion of each shell before the collision, and we find that a large part of the total energy of the shell, that initially resides mainly in the electromagnetic field, is transfered to bulk kinetic energy, yielding highly relativistic speeds. At large distances from the central engine, the magnetic field is found to be mainly azimuthal, still carrying a non-negligible part of the total energy. If the relative speed between two adjacent shells is higher than the fast magnetosonic speed in both fluids, the collision propagates through two shock waves, which in the center of mass system move in opposite directions – see Fig. 1. A contact discontinuity is also formed.

In order to describe the shocked regions (2, 3) we assume that the plasmas are ideal ($\boldsymbol{E} = -\boldsymbol{\beta} \times \boldsymbol{B}$), and – since the magnetic field is mainly azimuthal – the shocks are perpendicular. We use a parameter $k = \beta_{2s} B_{2s}/(\beta_{1s} B_{1s})$ which is related to the ratio of the magnetic energy in the shocked to the one in the unshocked region [6, 7] to allow for possible dissipation when the plasma crosses the discontinuity through some unknown microscopic process.

Using the above assumptions we set the equations that describe the collision, which, besides the dissipation parameter for the forward ($k_{\rm for}$) and the reverse shock ($k_{\rm rev}$), consist of the jump conditions for mass, momentum and energy in the two shocks, the total pressure-balance at the central discontinuity, the plastic collision requirement $\gamma_2 = \gamma_3$, and a polytropic equation between pressure and energy density, $P = (\hat{\Gamma} - 1)e$. In this paper we further assume that $k_{\rm for} = k_{\rm rev} = k$ (although the values of k in the two shocks are different, in general). The manipulation of the shock jump conditions leads to a simple polynomial equation for the compression ratio that can be solved numerically for different values of the dissipation parameter. Using finally the continuity of the total pressure ($P + B^2/8\pi$) at the contact discontinuity we determine the value of k – see Fig. 2. Note that there are cases in which the equation of pressures cannot be satisfied for any value of k. The requirement for a common value of k is rather restrictive; the reason lies on the assumption that the magnetic energy is forced to be dissipated by the same percentage in the two shells and this is not always consistent with the conservation of momentum.[1]

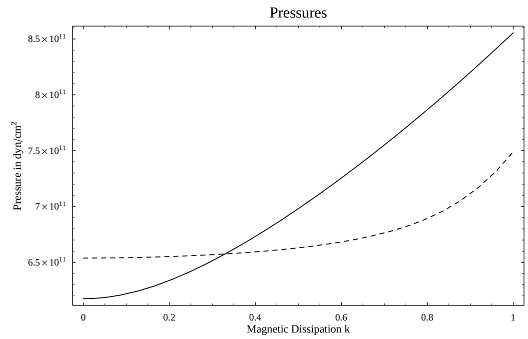

Figure 2: The total pressure of each shocked region (solid for region 2 and dashed for region 3) as a function of the magnetic dissipation parameter. The curves intersect, meaning that a unique value of k is consistent with the collision.

Prompt Emission Spectrum

Having specified the values of all physical quantities in the shocked region we can obtain self-consistently the radiated spectrum. We assume that the thermal energy released after the plastic collision of the two shells is transferred mainly into random kinetic energy of the protons, which obtain a relativistic Maxwellian distribution. In the shocked region of the fast shell the initial proton energy density is high enough to trigger sufficient energy losses through proton-proton interactions. Thus, energy is carried into photons, electron-positron pairs and neutrinos through the decay of neutral and charged pions and, consequently, numerous other physical processes between them start taking place. In order to derive the spectrum, we follow the work of [8] and solve three coupled kinetic equations which describe the time evolution of high energy protons, electrons and photons in the system. The physical processes we include in the kinetic equations are:

1. *proton-proton interactions*,
2. *proton-photon interactions*,
3. *synchrotron radiation*,
4. *synchrotron self-absorption*,
5. *inverse Compton scattering*,
6. *photon downscattering on cooled pairs*,
7. *photon-photon pair production*,
8. *electron-positron annihilation*.

The hadronic cascade that ensues can be described briefly as follows: At the first stages protons inter-

1. We investigate cases with $k_{\rm for} \neq k_{\rm rev}$ in Sapountzis et al, in preparation.

act with each other and start producing pions which decay into high energy photons, electron-positron pairs and neutrinos. While neutrinos escape, the pairs will lose their energy through synchrotron radiation and the π^0-produced γ-rays will be absorbed by the synchrotron photons producing more pairs which will radiate further synchrotron photons. As a result, the photon density grows rapidly (i.e. within one source crossing time), therefore photon-dominated processes like inverse Compton scattering and proton-photon interactions become important adding to the electron and proton losses respectively. Finally photon down-scattering on cooled electrons and electron-positron pair annihilation have a contribution to the spectrum.

As the above processes take place, the source expands adiabatically. Due to the fact that all rates which enter the equations depend critically on the densities of particles and photons we find that the maximum of the emission will be at timescales of comparable to the light crossing time of the source.

In the next paragraph we show some characteristic results of our model calculations.

Results

As an example, we present a case of a collision of two shells where a value of magnetic dissipation k exists. The parameter values in the regions (1, 2, 3, 4) of Fig. 1, in their co-moving frame, are:

Region 1 *(Unshocked fast blob)*

proton density $\rho_1 = 3.7 \times 10^{-10}$ g/cm^3

proton energy density $e_1 = 3.78 \times 10^8$ erg/cm^3

Lorentz factor of the flow $\gamma_1 = 525$

magnetic field $B_1 = 1.35 \times 10^6$ G

Region 2 *(Shocked fast blob)*

proton density $\rho_2 = 3.77 \times 10^{-10}$ g/cm^3

proton energy density $e_2 = 2.14 \times 10^{12}$ erg/cm^3

Lorentz factor of the flow $\gamma_2 = 450$

magnetic field $B_2 = 4.4 \times 10^6$ G

Region 3 *(Shocked slow blob)*

proton density $\rho_3 = 4.15 \times 10^{-10}$ g/cm^3

proton energy density $e_3 = 2 \times 10^{10}$ erg/cm^3

Lorentz factor of the flow $\gamma_3 = 450$

magnetic field $B_3 = 1.57 \times 10^6$ G

Region 4 *(Unshocked slow blob)*

proton density $\rho_4 = 2.85 \times 10^{-10}$ g/cm^3

proton energy density $e_4 = 2.68 \times 10^8$ erg/cm^3

Lorentz factor of the flow $\gamma_4 = 383$

magnetic field $B_4 = 1.2 \times 10^6$ G

We note that the proton energy density e is directly related to the temperature T of each flow region through the relation $e = 3nk_BT$, where n is the proton number density. Based on the set of values given above, we find that among the two shocked regions, only in the region (2) of the fast shell protons have acquired a Maxwell distribution with enough average energy $\gamma_p = 3k_BT/m_pc^2 \simeq 6.3$ to spark off all the physical processes that can lead to the prompt emission spectrum. Thus, in the region (2), which has a radius $R = 5.5 \times 10^{10}$ cm, we solve the system of the kinetic equations and we evaluate the photon and neutrino spectra.

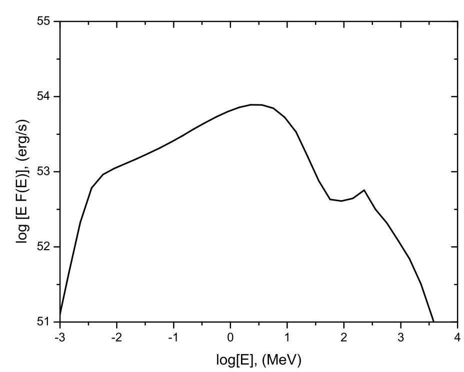

Figure 3: Differential photon luminosity at peak of emission, in the laboratory frame.

In Fig. 3 we show the photon spectrum, as obtained in the laboratory system at the peak of emission which occurs at about one crossing time after the thermalization of the energy (for the present case $t_{\rm cr} = R/c = 1.84$ s in the comoving frame). The spectrum shows a peak energy at $E_{\rm peak} \sim 2.3$ MeV. The part of the spectrum below $E_{\rm peak}$ is mainly formed through synchrotron radiation of electron-positron pairs produced either from the decay of charged pions in pp collisions or directly

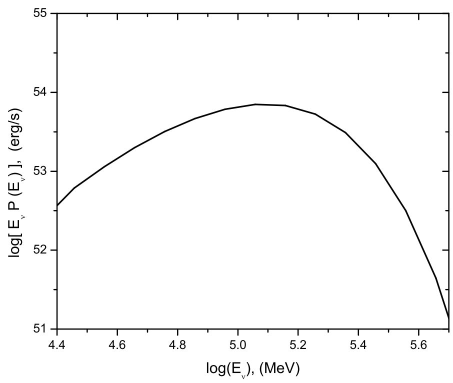

Figure 4: Differential luminosity of neutrinos as a function of their energy E_ν at the peak of photon emission as measured in the laboratory system.

through $\gamma\gamma$ interactions. A (blueshifted) annihilation line can also be seen.

In Fig. 4 we show the neutrino spectrum which corresponds to the peak of the photon emission depicted in Fig. 3. As neutrinos escape without any absorption from the system, their spectrum peaks at much higher energies than that of the photons which undergo severe reprocessing.

In this typical example the luminosities are $L_\gamma \sim 3.7 \times 10^{54}$ergs s^{-1} for the photons and $L_\nu \sim 10^{54}$ergs s^{-1} for the neutrinos – as we have already mentioned these values are estimated at one crossing time after the proton thermalization. We also find that within this timescale the proton energy has decreased from $E_{p,o} \sim 1.5 \times 10^{45}$ ergs that was initially to $E_p \sim 1.2 \times 10^{45}$ ergs. In other words, protons have lost almost ~ 21 % of their energy in this short period of time.

Conclusions

In this paper, we have considered a simple model in order to investigate the internal shock formation in GRB outflows and the prompt emission spectrum. First, we followed the acceleration of each outflow-shell using magnetohydrodynamics, and the plastic collision between two magnetized shells, taking into account possible dissipation of magnetic energy. We modeled this process using a parameter k, whose value is found with the use of the jump conditions in the shocks and the contact discontinuity. Within this procedure we find that a substantial amount of energy is released in thermal form and is transferred into the shocked plasma. Then, we formed and solved a highly non-linear system of kinetic equations describing the interactions between protons, electron-positron pairs, photons, and the strong magnetic field, and we derived the radiated photon and neutrino spectra self-consistently.

Acknowledgements

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