LIGHT CURVES AND SPECTRA FROM GAMMA RAY BURSTS

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ABSTRACT

We present simulations of the complete evolution of a fireball model for gamma ray bursts using a relativistic hydrodynamic code. Particle acceleration at both the forward and reverse shocks produces energetic electrons which then emit synchrotron radiation in the ambient magnetic field. The observed synchrotron spectra and light curves are calculated.

1. INTRODUCTION

Fireball models for GRB sources involve the sudden release of energy in the form of an optically thick $e^{\pm}$ plasma. The plasma along with its radiation expands out to to the point where it becomes optically thin and the radiation is released. The presence of an additional baryonic component results in the conversion of some or all of the initial energy in to the kinetic energy of an expanding shell of matter. Forward and reverse shocks will then form heating up both the swept up external matter and the shell of matter. Variabilty in the central "engine" of the fireball may also lead to the formation of internal shocks in the ejecta.

In this paper we study the hydrodynamics of the forward and reverse shocks including the point at which the reverse shock has propagated back into the origin of the explosion and is reflected back out again. We have developed a numerical scheme to study this process and the details are contained in section (2). Electrons will be accelerated by the shock acceleration mechanism and will then emit synchrotron radiation in the ambient magnetic field. We assume that a small fraction of the thermal energy density is converted into energetic electrons and magnetic field energy at the point at which the flow is shocked. Subsequently the electrons lose their energy via synchrotron and adiabatic losses. In section (3) we discuss the initial conditions while in section (4) we present results for the hydrodynamics light curves, and spectra which would be observed.

2. METHOD

Here we briefly describe the code used in this work. A more complete description, along with a description of the tests performed on the code, can be found in Downes et al. (2000).

2.1. The Hydrodynamics

The conservation equations for relativistic hydrodynamics in spherical symmetry are

$$\frac{\partial}{\partial t}(\Gamma\rho) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\Gamma\rho\beta\right) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}\left(w\Gamma^2\beta\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w\Gamma^2\beta^2 + p\right)\right] = \frac{2p}{r} \quad (2)$$

$$\frac{\partial}{\partial t}\left(w\Gamma^2 - p\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 w\Gamma^2\beta\right) = 0 \quad (3)$$

where Γ is the fluid Lorentz factor, ρ is the proper density, β is the velocity in $c = 1$ units, w is the enthalpy and p is the proper pressure. Time, t, and distance, r, refer to the coordinates measured in the observer's frame.

A 1 dimensional, spherically symmetric, second order MUSCL-type scheme (van Leer, 1977) is used to integrate these equations for the expansion of a relativistic blastwave into the interstellar medium. The enthalpy, density, and pressure are related with the assumption that the gas behaves as a Synge gas. Hence the ratio of specific heats varies from $\frac{4}{3}$ for a relativistically hot gas, to $\frac{5}{3}$ for a non-relativistic gas.

A linear Riemann solver is used to compute the fluxes of the conserved variables across the cell interfaces unless there is a strong double rarefaction present, in the which case a nonlinear solver is used (following Falle and Komissarov, 1996).

2.2. The Synchrotron Emission

In order to simulate the synchrotron emission from the fluid flow we have introduced 3 free parameters (assumed to be constant in space and time):

- $\epsilon_b = 0.01$: The ratio between the magnetic field energy density and the thermal energy density.
- $\epsilon_e = 0.01$: The fraction of thermal energy injected into energetic electrons at the shock.
- $\epsilon_p = 0.01$: The fraction of thermal electrons which are accelerated into the energetic population at a shock.

The values for ϵ_b and ϵ_e are consistent with those found by Wijers & Galama (1999).

We assume that energetic electrons are produced at shocks with a power-law distribution in energy from $\Gamma_0 = 2$ to infinity. The exponent of the distribution is taken as 2.5. The electrons are then assumed to be advected with the flow. Two parameters of the distribution are tracked - one is a function of the density of the fluid element into which the particles were injected and Γ_0, and the second is the integral of the square of the magnetic field, following the fluid element. These two parameters allow us to track the population of energetic electrons throughout the flow, incorporating the effects of synchrotron and adiabatic cooling.

The resulting electron distribution is used to calculate the synchrotron emission spectrum from a particular point in space. This is then integrated over space with the requirement that the arrival time for photons from any point in the simulation be the same. Thus the effects of light travel-time discussed in Sari (1998) are incorporated into the results presented here, as are the relativistic Doppler effect, and the effects of relativistic beaming. We do not take account of synchrotron self-absorption.

3. INITIAL CONDITIONS

Initially, a sphere of high pressure and high density gas exists within a radius $R_0 = 1.2 \times 10^{14}$ cm of the origin. The pressure and density are chosen so that the energy inside this sphere is 10^{51} ergs, and the energy to mass ratio, η, is 550. These parameters ensure that the radius at which the blast wave begins to decelerate (i.e. when it has swept up its own mass of ambient material), R_d, is equal to the radius at which it has accelerated to its maximum velocity, R_c.

The energy chosen is slightly lower than the energy thought to be released in gamma ray bursts (if the bursts are isotropic) and this is to avoid some numerical difficulties when the reverse shock begins propagating inward towards the origin.

The physical size of the grid is 4.7×10^{17} cm with 10^5 equally spaced grid points. The observer of the blast is assumed to be very far away so that $\frac{L}{R}$, the ratio of the distance of the observer to the radius of the blast, is assume to be much greater than 1 for all time. The ambient density is set to 1 cm^{-3}. The ambient temperature is $\sim 10^{10}$ K which is, of course, extremely hot for the interstellar medium. However, the pressure this corresponds to is not dynamically important for the duration of the simulations presented here. There will, however, be a small error in the blastwave shockspeed as the value of the ratio of specific heats is 1.5 rather than $\frac{5}{3}$. However, the results can be expected to be more accurate than, e.g., Kobayashi et al. (1999) where a constant ratio of specific heats of $\frac{4}{3}$ is assumed.

4. RESULTS

We present the results in three parts. The first deals with the hydrodynamic evolution of the blastwave, the second with the spectra calculated, and the third with the simulated light curves.

4.1. Hydrodynamics

Figures 1 and 2 show the proper density, 4-velocity, and pressure at $t = 5 \times 10^6$s and 1×10^7s. We can see that in figure 1 the reverse shock has begun propagating back towards the origin of the blast. Both the forward and reverse shocks are relativistic in the sense that the gas is heated to give a ratio of specific heats of $\frac{4}{3}$. In the density plot it can be seen that there are some entropy errors just behind the reverse shock. These have their origin in the extremely strong rarefaction which accompanies the initial expansion into the ambient medium. They are mild errors and do not significantly affect either the dynamics or the synchrotron emission presented here.

At $t = 1 \times 10^7$s we can see that the reverse shock has reflected back from the origin and is propagating outwards again, although by now it is greatly weakened. The forward shock has also weakened, but it is still mildly relativistic.

Figure 3 shows a plot of the maximum lorentz factor reached *versus* distance. We can see that the blastwave never reaches the predicted maximum $\Gamma_{\max} \approx \eta$, but this is to be expected since this value is based on the blastwave expanding into a perfect vacuum. In more realistic scenarios, then, sweeping up of ambient material means that η is an upper limit for $\Gamma_{\max}$. $\Gamma_{\max}$ approaches this upper limit as $\frac{R_c}{R_d} \to \infty$ (see Sect 3).

4.2. Spectra

The spectra are calculated at 24 equally spaced times starting 1 hour after the blast could initially be ob-

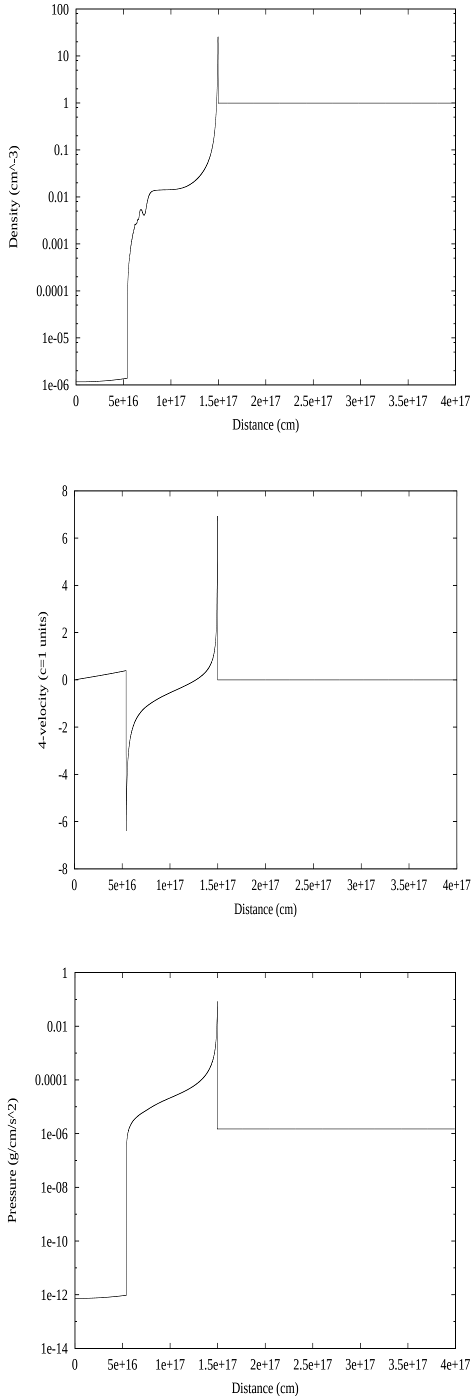

Figure 1. Plots of the proper density (top), 4-velocity (middle), and pressure (bottom) at time $t = 5 \times 10^6 s$

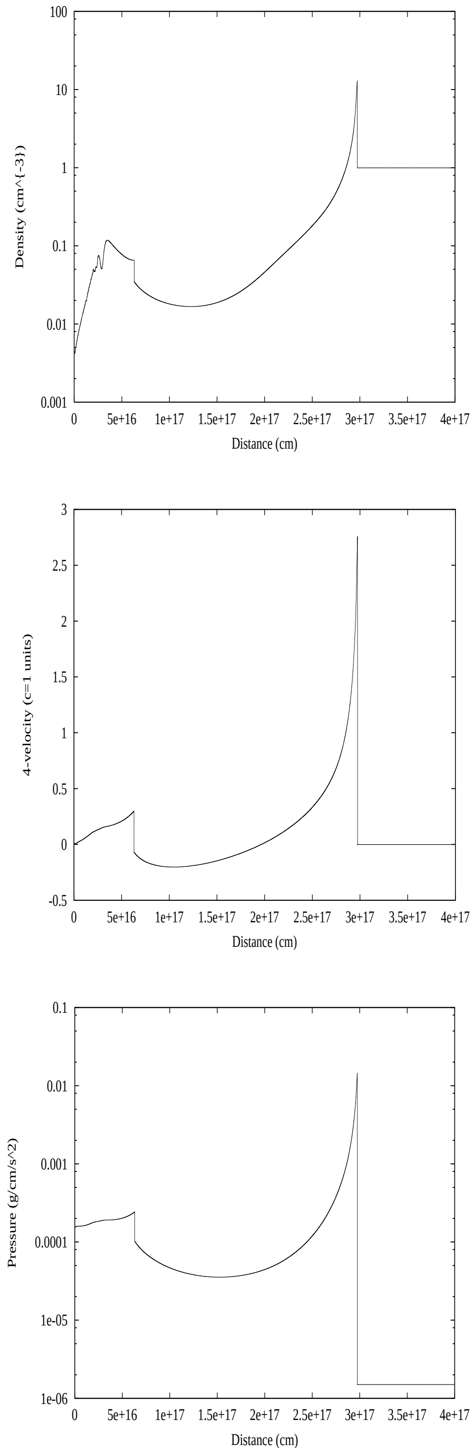

Figure 2. As in figure 1 at time $t = 1 \times 10^7 s$

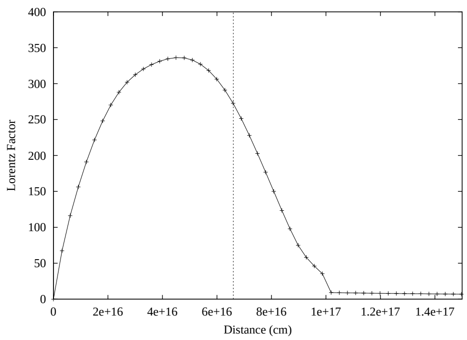

Figure 3. Plot of the maximum Lorentz factor versus distance. The vertical line marks where the mass in the initial blast is equal to the mass of swept up ambient material. See text.

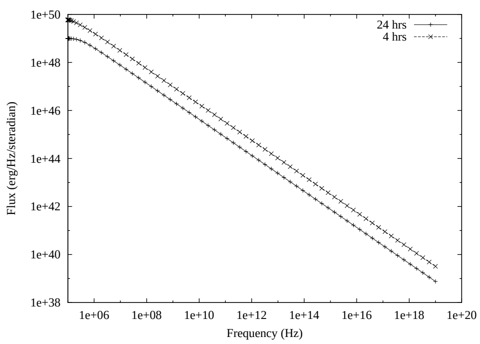

Figure 4. Sample synchrotron spectra for 4 hrs and 24 hrs after the blast is initially observed.

served. The observation times of the spectra are separated by 1 hour. The range of the spectra is $[1 \times 10^5, 1 \times 10^{19}]$ Hz. It was found that the slope of the spectrum is constant at -0.75 (i.e. the uncooled synchrotron spectrum) for the duration of these simulations. Hence synchrotron cooling (and also adiabatic cooling) has a negligible effect on the observations of the type of explosion simulated here, at least for observational time-scales of a day or so. A sample spectrum is shown in figure 4.

4.3. Light curves

Figure 5 shows the light curve which would be observed at a frequency of 3×10^6 Hz. The light-curves are similar at all frequencies, with the exception of high frequencies where the initial conditions affect the emission at early times. The flux grows until a time of approximately 3 hrs after the initial signal from the blast reaches the observer. It then decays as a power-law with exponent of ≈ -1.

5. DISCUSSION

We have run simulations with initial conditions appropriate to the fireball model of GRBs. We have

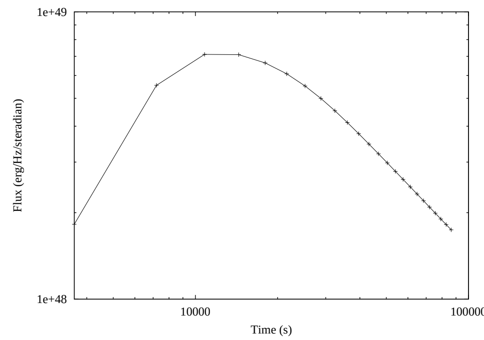

Figure 5. Plot of the flux at a frequency of 3×10^6 Hz as a function of time. See text.

also calculated the synchrotron emission in a fairly rigorous way, with the only assumptions being the constancy of ϵ_b, ϵ_e, and ϵ_p, and that energetic electrons are initially produced as a power-law in energy with exponent -2.5.

We have found that the slope of the spectrum remains constant over the first day of observations, with the primary contribution to the flux coming from uncooled electrons. There is no break in the spectrum, although it does flatten somewhat towards low frequencies ($f \sim 1e+05$ Hz).

The light-curves calculated here show an increase in intensity of emission until about 3 hrs after the blast is initially observed, followed by a power-law decay with exponent of -1. This is somewhat shallower than would be expected from the evolution of the uncooled electrons alone (see e.g. Galama, 2000).

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