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Afterglow Radiation from Gamma Ray Bursts

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ABSTRACT

Afterglow Radiation from Gamma Ray Bursts. HUGH DESMOND (Katholieke Universiteit Leuven, Leuven, Belgium) WEIQUN ZHANG (Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center, Stanford, CA 94025)

Gamma-ray bursts (GRB) are huge fluxes of gamma rays that appear randomly in the sky about once a day. It is now commonly accepted that GRBs are caused by a stellar object shooting off a powerful plasma jet along its rotation axis. After the initial outburst of gamma rays, a lower intensity radiation remains, called the afterglow. Using the data from a hydrodynamical numerical simulation that models the dynamics of the jet, we calculated the expected light curve of the afterglow radiation that would be observed on earth. We calculated the light curve and spectrum and compared them to the light curves and spectra predicted by two analytical models of the expansion of the jet (which are based on the Blandford and McKee solution of a relativistic isotropic expansion; see Sari's model [1] and Granot's model [2]). We found that the light curve did not decay as fast as predicted by Sari; the predictions by Granot were largely corroborated. Some results, however, did not match Granot's predictions, and more research is needed to explain these discrepancies.

INTRODUCTION

The timespan of gamma-ray bursts is relatively short, being between tenths of seconds and one thousand seconds. They are very energetic, despite being short, and they are the brightest known source of gamma-rays in the universe. They even outshine the sun in the gamma-frequency range, which is amazing considering that they occur at cosmological distances, i.e. outside of the Milky Way. It is estimated that a typical GRB releases 10^{52} ergs, which is as much energy as all the energy the Sun would radiate during its entire 10 billion year lifetime.

Despite the fact that most energy is released during the first seconds, there is still some emission of radiation after the initial outburst has subsided. There is a residual radiation at X-ray to radio frequencies, which is called the afterglow radiation. This afterglow is much fainter than the initial gamma-ray outburst, and is observable for up to tens of years.

It is a reasonable question to ask what physically causes this big flux of gamma-rays. There is a general consensus that a gamma-ray burst is a witness to a cataclysmic event concerning very compact objects, although the details of the event depend on whether the GRB is 'short' or 'long'. Short GRBs (with durations of $0.1 - 2$s) are thought to be caused by the collision and merging of two very compact objects (such as two neutron stars), which causes a twin jet of plasma to be ejected at highly relativistic speeds along the mutual rotation axis. The jet consists of several shock fronts, moving at different relativistic speeds. When one shock front catches up with another, they collide and energy is emitted in the form of gamma-rays, which we observe. Long GRBs (with durations of $2 - 1000$s) are presumably caused by the collapse of a massive star into a black hole, also causing a twin jet of plasma to be shot off along the rotation axis at relativistic energies. These twin jets also emit the gamma radiation we observe.

The afterglow radiation is caused by a mechanism separate from that governing the gamma-ray radiation. When the twin jets hit the surrounding interstellar medium, they cause the electrons in that medium to accelerate to relativistic speeds. Then, due to the magnetic field in the plasma jet, these electrons will emit synchrotron radiation. This synchrotron radiation is what will be calculated in this paper.

Studies have already been done on the radiation from GRB afterglows. Early studies simplified the problem, for example by just considering the radiation from one (representative) point [3], or by considering all points, but approximating the dynamics of the jet as the radial expansion of a cone (see [4]), thus neglecting the sidewards expansion. Another study [5] has tried to take the sidewards expansion into account by making the simplifying assumption that the speed of the sidewards expansion is uniform over θ, the opening angle of the jet. In all these studies these simplifying assumptions were made so an analytical model of the expansion of the jet could be used (this is the Blandford-McKee solution of the ultra-relativistic expansion of a spherical blast wave, see [6]).

In this paper the calculation will be presented based on a numerical model of the dynamics of the jet. This model is a hydrodynamical simulation of how the jet expands (since the jet is a plasma, it shows many similarities with a fluid). The simulation was run by W. Zhang and A. MacFayden on the NASA Colombia supercomputer, and presents a high resolution description of the expansion of the jet. Before going into the light curve and spectrum of the afterglow that we obtained, we will first dwell on the methods we used to calculate the synchrotron radiation.

MATERIALS AND METHODS

In this section we will break down the formalism into three basic steps. First we will calculate the synchrotron radiation power coming from a single electron. After that, we will calculate the power per unit frequency coming from the jet, which is a distribution of electrons; finally we will transform this emitted power into the observer frame to obtain the observed flux. We will now elaborate on these steps.

To calculate the radiation emitted by an electron in the jet, it would be sufficient to know what the magnetic field would be at every point and what the speed would be of every single electron. We then would be able to calculate the power through

$$P(\gamma_e, \nu) = \frac{\sqrt{3}}{2\pi} \frac{q_e^3 B \sin\alpha}{m_e c^2} \nu/\nu_0 \int_{\nu/\nu_0}^{\infty} K_{5/3}(\eta) d\eta, \tag{1}$$

where q_e is the electron charge, m_e is the electron mass, $K_{5/3}$ is the modified Bessel function of the second kind, α is the angle between the velocity and the acceleration of the electron. The reference frequency ν_0 is defined as $\nu_0 = \frac{3}{2} \frac{q_e B \sin\alpha}{mc} \gamma_e^2$.

However, this microphysics is unknown at present. The hydrodynamical simulation can give us the total internal energy e_{int}, the particle density n and the bulk velocity of the jet $\boldsymbol{\beta} = \boldsymbol{v}/c$. We make use of this, and make the assumption that the magnetic energy density, e_B, is a fixed fraction, ϵ_B, of the total internal energy density:

$$e_B = \epsilon_B e_{int}. \tag{2}$$

The strength of the magnetic field can then be easily estimated through $\frac{B^2}{8\pi} = e_B$. We make a similar assumption concerning the movement of the electrons within the jet. We assume that the electron energy density, e_e is also a fixed fraction, ϵ_e of the total energy density:

$$e_e = \epsilon_e e_{int}. \tag{3}$$

Then the average gamma factor, $<\gamma_e>$ of the electrons can be estimated through $n <\gamma_e> m_e c^2 = e_e$. For our calculation, we considered an adiabatic case by taking the values $\epsilon_B = \epsilon_e = 0.1$, so that the radiation had a negligible effect on the total energy of the jet.

The estimation of B and $<\gamma_e>$ allows us to calculate the power emitted per unit frequency per electron, as stated in equation 1 and visualized in figure 1. The frequency at which an electron will emit radiation depends on its speed while it is swirled around by the magnetic field; that is why a characteristic synchrotron frequency can be associated with a speed and this is done by the relation

$$\nu(\gamma_e) = \frac{q_e B}{2\pi m_e c}\gamma_e^2, \tag{4}$$

where q_e is the electron charge.

To calculate the radiation coming from the jet, we have to make another assumption, this time concerning the specific distribution of the electron energies. We assume that the distribution of the electron energy follows a power-law:

$$N(\gamma_e) \sim \gamma_e^{-p}, \quad \gamma_e \geq \gamma_{min}, \tag{5}$$

where the spectral index $p > 2.5$ (in our calculation we used $p = 2.5$) and $N(\gamma)d\gamma$ is the number of electrons per unit volume with energy between $\gamma m_e c^2$ and $(\gamma + d\gamma)m_e c^2$. This energy distribution has been found by previous studies to lead to predictions of the afterglow radiation that fit the observations.

All we need to do now is integrate the power per frequency per electron over the energy distribution to get the power per unit volume, per unit frequency:

$$P(\nu) = \int_{\gamma_{min}}^{\infty} P(\gamma_e, \nu) N(\gamma_e)\, d\gamma_e. \tag{6}$$

A slight complication arises in calculating the previous integral because the formula for $P(\gamma_e, \nu)$ (equation 1) is no longer valid when the electrons have a very high gamma factor and thus are rapidly losing a significant fraction of energy[1]. This regime where electrons lose energy rapidly is called the fast cooling region (as opposed to the slow cooling region). The demarcation between the two regions is at the cooling gamma factor, γ_c.

We will not go into the details of the evaluation of this integral; for further reference see [7] for the calculation without the complication of fast cooling and see [1] and especially [8]

[1] The synchrotron power emitted goes as γ_e^4, whereas the total energy goes as γ_e. So the higher γ_e is, the faster energy is radiated.

for a discussion of the radiation with fast cooling. When all the electrons are cooling fastly, $\gamma_{min} > \gamma_c$ and we have

$$P(\nu) = \begin{cases} P_{\nu,max}(\nu/\nu_c)^{1/3} & \nu < \nu_c \\ P_{\nu,max}(\nu/\nu_c)^{-1/2} & \nu_c < \nu < \nu_{min} \\ P_{\nu,max}(\nu_{min}/\nu_c)^{-1/2}(\nu/\nu_{min})^{-p/2} & \nu > \nu_{min}, \end{cases} \tag{7}$$

where ν_c is the cooling frequency, and is the frequency associated with the cooling gamma factor through equation 4. Conversely, when $\gamma_{min} < \gamma_c$,

$$P(\nu) = \begin{cases} P_{\nu,max}(\nu/\nu_{min})^{1/3} & \nu < \nu_{min} \\ P_{\nu,max}(\nu/\nu_{min})^{-(p-1)/2} & \nu_{min} < \nu < \nu_c \\ P_{\nu,max}(\nu_c/\nu_{min})^{-(p-1)/2}(\nu/\nu_c)^{-p/2} & \nu > \nu_{min}, \end{cases} \tag{8}$$

where $P_{\nu,max}$ is the peak frequency. To complete the second step, we need to integrate $P(\nu)$ over the jet region.

Finally we transform the power into the observer frame. The flux from that cell that reaches an observer on earth is

$$F(\nu', t') = \frac{1+z}{4\pi d_l^2} \int \frac{P(\nu, t)}{\gamma^2(1 - \boldsymbol{\beta} \cdot \boldsymbol{n})^2} 2\pi r^2 \sin\theta \, d\theta dr, \tag{9}$$

where d_l is the luminosity distance (which is, in this case, a measure of the distance to the source of the GRB), z the redshift and $\boldsymbol{n}$ a unit vector pointing towards the observer (on the rotation axis). The primed quantities t' and ν' denote the observer frame time and frequency. The relation between source and observer frequency is

$$\nu = \gamma(1 - \boldsymbol{\beta} \cdot \boldsymbol{n})(1+z)\nu', \tag{10}$$

which takes into account the redshift and doppler shift[2]. The relation between source and observer time is

$$t = t' - \frac{r\cos\theta}{c} \tag{11}$$

and accounts for the transit time of the flux.

RESULTS AND DISCUSSION

Figure 2 shows the calculated light curves for 8 representative frequencies, ranging from radio frequencies to optical and x-ray frequencies. The light curve of each frequency roughly follows a segmented power-law.

The break time is represented by the vertical dotted line. At that time, the jet no longer expands purely radially, but expands in a sidewards direction as well. One consequence of this is that the volume occupied by the jet increases more sharply, leading to a sharper drop in internal energy and a sharper drop in radiation emitted. Another consequence is that at that time all of the jet is seen and there is no further increase in the observed area of the jet. To understand this, consider the radiation of charged particles moving at relativistic speeds; the emitted photons are beamed, i.e. concentrated in a cone with an angle of $\theta_{rad} \sim 1/\gamma$, where γ is the gamma factor of the moving particle. So when the a part of the forefront of the jet is moving at relativistic speeds in radial direction, the radiation is concentrated in a cone along the direction of the speed. As the jet slows down, the radiation is less concentrated, so the radiation from a increasingly large area of the jet actually reaches the observer. When the jet finally breaks, $\theta_{rad} \approx \theta_{jet}$, where θ_{jet} is the opening angle of the jet, and the observer can see the radiation coming from all areas of the jet. Thus there will be no contribution from the fact that radiation from an increasingly large area is reaching the observer; the subsequent drop in radiation will therefore be sharper than before the jet break.

Before the break, the flux goes as $t^{1/2}$ for low frequencies and as $t^{(2-3p)/4}$ for high fre-

[2] Note that $\gamma = (1-\beta^2)^{-1/2}$ is the bulk gamma factor of the jet and is not the same as the γ_e, the gamma factor of an electron.

quencies. After the break, all frequencies go as t^{-p}. At later times, we find that the decrease in flux is less steep than predicted by the analytical model. This is partially due to the fact that we have taken the effect of the counter-jet into account. At later times, the radiation coming from the counter-jet is visible, and this accounts for the 'bump' in the flux at around 5000 days.

If we compare the behavior of the flux after the break with the predictions of Sari's analytical model, see [1], and which is represented in the figure by the dotted lines, we find that our calculated flux shows a decay that is significantly steeper than the decay predicted by Sari, both for low frequencies and high frequencies. However, there is quite a good agreement with Granot's analytical model, which is represented by the dash-dot lines. This result thus corroborates Granot's model at the expense of Sari's model. As mentioned above, at later times the decay does seem as rapid as predicted by Granot's model, even when we account for the contribution from the counter-jet.

The spectrum of the afterglow is represented in figure 3. The break in the power-law occurs at $\nu = \nu_c$. The cooling frequency shifts to higher frequencies at later times, which is reasonable, because it means that fewer electrons are in the fast cooling region as time progresses. In general, the calculated spectrum agrees extremely well with the predictions of both analytical models.

CONCLUSION

We have calculated both the observed light curves and spectra from the afterglow radiation. In the calculation we used data from a numerical hydrodynamical simulation of the jet, and assumed a power-law distribution of electron energy. Furthermore we made assumptions concerning the microphysics of the jet so that we could estimate the magnetic field and the movement of the electrons within the jet.

We compared the light curve to Sari's model and found the decay of the light curve to be significantly different. In contrast, the calculated light curve agreed very well with Granot's predictions. The calculated spectrum agreed well with both Sari's and Granot's predictions.

More research is needed to fully explain all the features of the results, such as the discrepancy at later times between our calculated light curve and Granot's prediction. More research is also needed to fully exploit the numerical simulation. We did the calculation for a jet where the energy and density are distributed uniformly over the opening angle. This is not realistic, and in the future the calculation could be done for a jet where the energy and density follow a non-uniform distribution (such as a Gaussian distribution).

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FIGURES

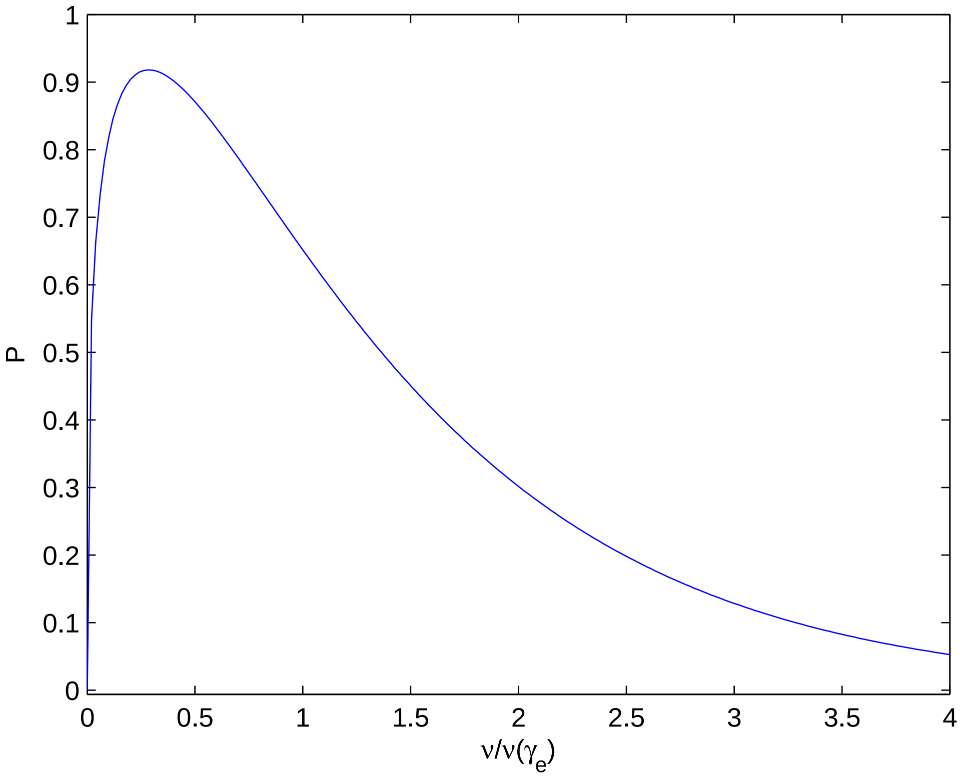

Figure 1: Synchrotron radiation of an electron. The power goes as $(\nu/\nu(\gamma_e))^{1/3}$ for $\nu \ll \nu(\gamma_e)$ and drops exponentially for $\nu \gg \nu(\gamma_e)$.

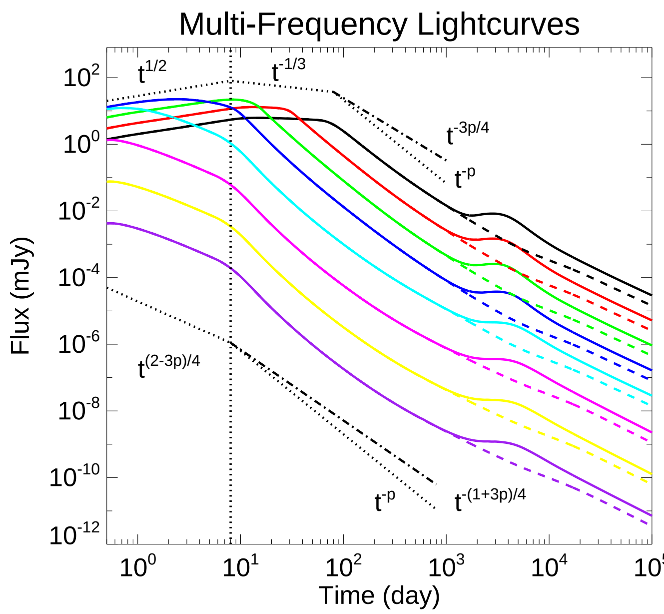

Figure 2: The calculated light curves per frequency are represented by the solid lines. The frequencies range from 10^9Hz for the black line, to 10^{18} Hz for the violet line. The dashed line is the calculated flux without taking the contribution from the counter jet into account. The dotted lines are the light curves predicted by Sari's model, whereas the dash-dot lines are the light curves as predicted by Granot's model. The dotted vertical line represents the break time.

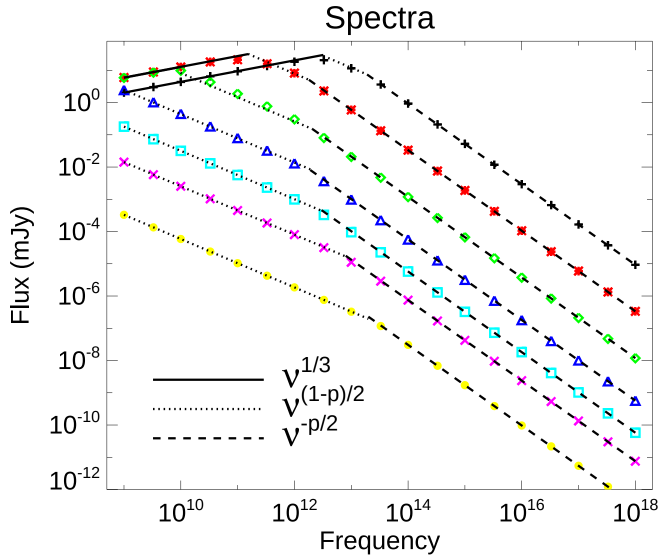

Figure 3: The colored dots represent the fluxes calculated in this study. The predictions from the analytical models are shown in the dotted lines.