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Early Gamma-Ray Afterglow from Gamma-Ray Bursts

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We show simulation results of multi-wavelength emission from gamma-ray burst afterglows. Our numerical code can follow the temporal evolution of the electron energy distribution in the forward shock region with injection, radiative cooling, and adiabatic cooling. Our exact treatment can generate the evolutions of synchrotron and SSC spectra. Depending on the CSM density profile, and microscopic parameters, a variety of gamma-ray lightcurves are predicted. Those results can be compared with future observations with MAGIC, H.E.S.S., VERITAS, CTA, HAWC, Alpaca, and LHAASO.

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1. Introduction

The afterglow of gamma-ray bursts (GRBs) is an excellent target for studying particle acceleration in ultra-relativistic shock waves. To explain the nature of the afterglow, efficient energy transport from protons to electrons must occur in relativistic shock waves, and the magnetic field must also be amplified. A sharp low-energy cutoff is required for the electron energy distribution. However, even in the rapidly developing PIC simulations, such a clear cutoff is not seen [1]. Furthermore, it is not clear whether the amplification of the magnetic field is due to kinetically driven turbulence, such as the Weibel instability, or to macroscopic turbulence on the MHD scale. As described above, particle acceleration and magnetic field amplification in relativistic shock waves remain unsolved problems.

In many GRBs, the first few thousand seconds of X-ray afterglows often show a very gradual decay, which is called the shallow decay phase. In the most commonly discussed models, early afterglows cannot be represented by the point source explosion approximation, and energy is continuously injected into the shock wave propagating the circumstellar material in the early stage. Most of the GRBs for which Fermi-LAT has detected a gamma-ray afterglow do not have this shallow decay phase [2], and their X-ray afterglows decay as $\propto t^{-1}$ from the beginning. Even in GRBs accompanied with TeV afterglows, which have been detected successively in recent years, many of them do not show a shallow decay phase.

Further observations at multiple wavelengths, including TeV gamma rays with MAGIC, H.E.S.S., VERITAS, CTA, HAWC, Alpaca, and LHAASO, are essential to elucidate the behavior of early afterglows and particle acceleration in relativistic shock waves. In particular, TeV gamma-ray detections for GRB afterglows with a shallow decay phase will provide important information to determine the model. In this paper, we present various models that reproduce the shallow decay phase using time-evolving simulations and discuss how future TeV gamma-ray observations can determine the models.

2. Method

We use our numerical code used in [3, 4] to follow the time evolution of electron energy distribution in the shocked circumstellar material and calculate the multi-wavelength lightcurves for an observer. Our calculations are still preliminary and the details will be published in a journal in the near future. Here we briefly discuss the results of four models to show what kind of lightcurve behavior is observed: (1) the energy injection model, (2) the low Lorentz factor jet model propagating in a low-density stellar wind (see [5]), (3) a model in which the energy transport efficiency from protons to electrons increases with time, and (4) a model in which the amplification efficiency of the magnetic field increases with time. The latter two models may seem artificial, but we regard these as possible models in the current situation where the physics of relativistic shock waves is not well understood. The efficiency of the energy transport to electrons may be adjusted by pre-heating due to turbulence excited upstream, which would depend on the Lorentz factor of the shock wave and the magnetization upstream. The magnetization downstream of the shock wave may be also a function of such shock wave parameters, depending on the magnetic field amplification mechanism.

3. Results

As an example of the calculations, the multi-wavelength lightcurves for Model 1 are plotted in Fig. 1. The model parameters are the redshift $z = 0.5$, the initial Lorentz factor $\Gamma = 300$, the density of the circumstellar medium $n = 1$ cm^{-3}, the electron index at injection $p = 2.2$, and the fractions of the electron and magnetic energy densities, $\epsilon_e = 0.1$ and $\epsilon_B = 10^{-3}$, respectively. The energy of the shock wave increases proportionally to the square of the radius until $R = 3.2 \times 10^{17}$ cm, eventually reaching 10^{53} erg.

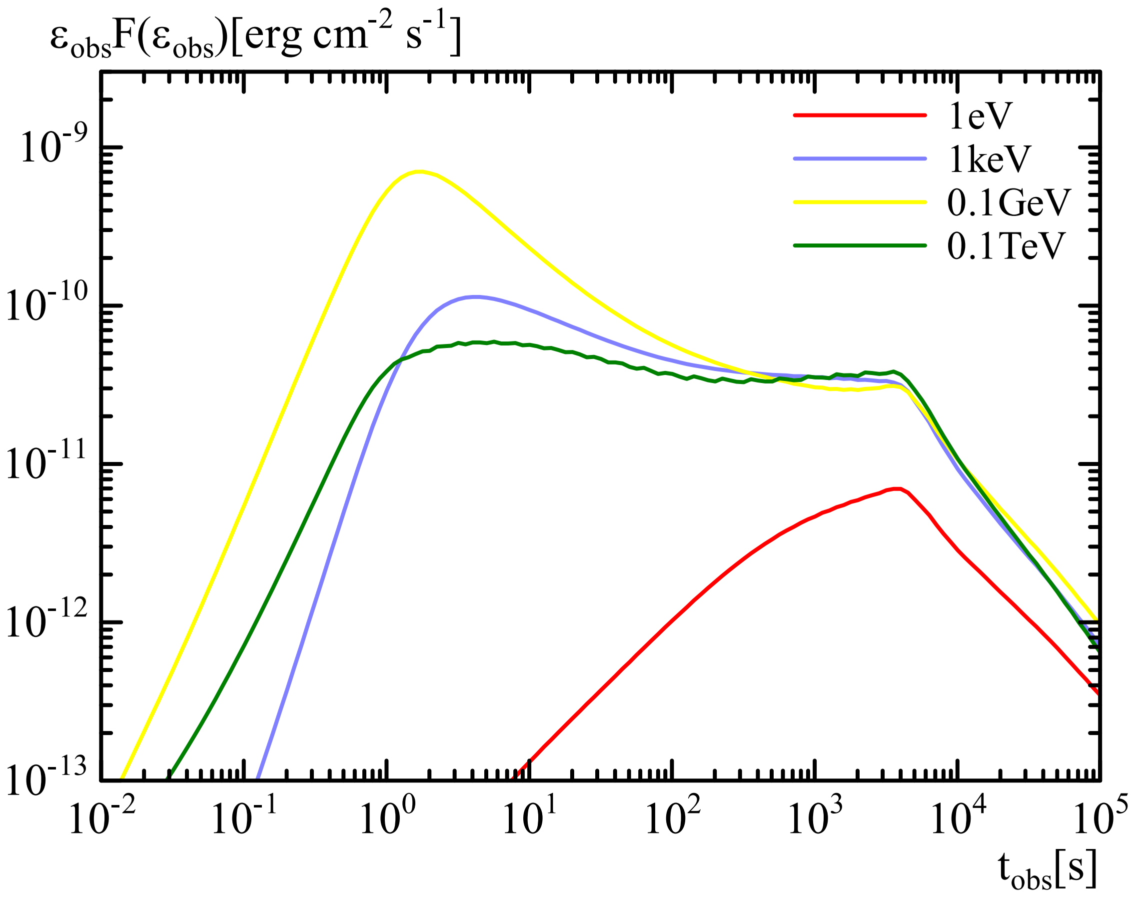

Figure 1: Multi-wavelength lightcurves for Model 1.

As shown in Fig. 1, the X-ray lightcurve shows a typical shallow decay behavior. The lightcurves of optical and TeV gamma rays in the four models are very different from each other. Since the optical afterglow may be dominated by the emission component from the reverse shock, gamma-ray lightcurves, which may be almost free from the reverse shock emission, will provide a strong clue to discriminate the models.

In the four models, the parameters are adjusted to common values after the end of the shallow decay phase to make the subsequent lightcurves nearly the same. The brightness of the TeV afterglow is then model 4, 1, 2, and 3, in that order. The brightness difference between the brightest and darkest models is nearly two orders of magnitude. Future observations of gamma rays can reveal the time evolution of GRB engine activity and/or the physics of relativistic shock waves.

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