Abstract

Recent detection of sub-TeV emission from gamma-ray bursts (GRBs) represents a breakthrough in the GRB study. The multiwavelength data of the afterglows of GRB 190114C support the synchrotron self-Compton (SSC) origin for its sub-TeV emission. We present a comparative analysis on the SSC emission of GRB afterglows in the homogeneous and wind environments in the framework of the forward shock model. The $\gamma\gamma$ absorption of very-high-energy photons due to pair production within the source and the Klein–Nishina effect on the inverse Compton scattering are considered. Generally a higher SSC flux is expected for a larger circum-burst density due to a larger Compton parameter, but meanwhile the internal $\gamma\gamma$ absorption is more severe for sub-TeV emission. The flux ratio between the SSC component and the synchrotron component decreases more quickly with time in the wind medium case than in the homogeneous density medium case. The light curves of the SSC emission are also different for the two types of media. We also calculate the cascade emission resulting from the absorbed high-energy photons. In the ISM environment with $n \gtrsim 1$ cm$^{-3}$, the cascade synchrotron emission could be comparable to the synchrotron emission of the primary electrons in the optical band, which may flatten the optical afterglow light curve at an early time ($t < 1$ hr). In the wind medium with $A_\text{s} \gtrsim 0.1$, the cascade emission in the eV–GeV band is comparable or even larger than the emission of the primary electrons at the early time.

1. Introduction

It was proposed that high-energy afterglows (>100 MeV) may result from the synchrotron radiation of the shock-accelerated electrons (e.g., Kumar & Barniol Duran 2009; Ghisellini et al. 2010; Wang et al. 2010), but the limit of a maximum synchrotron photon energy of about $50\Gamma/(1+z)$ MeV for a burst at a redshift of $z$ makes it difficult to explain the observed $\gtrsim$10 GeV gamma rays with the Fermi Large Area Telescope (LAT) at the time when the bulk Lorentz factor $\Gamma$ of the jet has decreased significantly (e.g., Piran & Nakar 2010). These $\gtrsim$10 GeV photons could then be produced by the synchrotron-self-Compton (SSC) emission in the afterglow shocks, which is supported by multiband modeling of some LAT-detected gamma-ray bursts (GRBs) (Wang et al. 2013), particularly the very bright GRB 130427A (Liu et al. 2013; Tam et al. 2013; Ackermann et al. 2014; Fraija et al. 2016). Indeed, afterglow SSC emission has been long predicted to be able to produce high-energy photons (e.g., Mészáros & Rees 1993; Waxman 1997; Chiang & Dermer 1999; Panaitescu & Kumar 2000; Sari & Esin 2001; Wang et al. 2001; Zhang & Mészáros 2001; Granot & Guetta 2003; Fan et al. 2008; Beniamini et al. 2015).

The multiwavelength data of GRB 190114C strongly support that sub-TeV photons are dominated by the SSC process (Derishev & Piran 2019; Fraija et al. 2019c; MAGIC Collaboration et al. 2019; Wang et al. 2019). The sub-TeV emission from GRB 180720B (Abdalla et al. 2019) can also be represented with the SSC model (Fraija et al. 2019b; Wang et al. 2019). The SSC emission is sensitive to the density of the external medium, which could be a homogeneous external medium or a stratified wind medium. In this work, we will investigate the differences in the SSC emission of afterglows arising from the two types of external media.

High-energy photons may be absorbed via the pair production process ($\gamma\gamma \rightarrow e^+e^-$) within the source, and the secondary $e^+e^-$ pairs could produce cascade emission via the synchrotron radiation and inverse Compton (IC) processes. The $\gamma\gamma$ absorption and pair cascade process have been widely studied in both blazars (Aharonian et al. 2008; Zacharopoulou et al. 2011; Yan & Zhang 2015) and the prompt emission of GRBs (Pe’er & Waxman 2005; Gill & Granot 2018). We here consider this effect in the afterglow phase of GRBs.

This paper is organized as follows. We compare the spectral energy distributions (SEDs) and light curves in two types of media in Section 2. The analyses of cascade radiation initiated by internal $\gamma\gamma$ pair production are presented in Section 3. Conclusions and discussions are presented in Section 4.

2. Broadband SEDs and Light Curves of GRB Afterglows in Homogeneous and Wind Media

Employing the standard dynamic evolution model for GRB afterglows (e.g., Huang et al. 1999), we derive the SEDs and light curves of the GRB afterglows by considering the afterglow emission is produced by electrons accelerated in the forward shocks expanding into the external medium. Two types of media were extensively studied, i.e., the homogeneous medium with a constant density ($n = n_0$; Sari et al. 1998) and the wind medium with a density profile of $n(r) = A r^{-2}$, where $A = 4\pi M V = 3.0 \times 10^{35} A_8 \text{ cm}^{-3}$ and $A_8 = M / 10^{-8} \text{ M}_\odot \text{ yr}^{-1}$, where $M$ is the mass loss rate of the massive star and $V$ is the constant wind speed for a Wolf–Rayet star (Dai & Lu 1998;
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Chevalier & Li 2000; Panaitescu & Kumar 2000). The radiation mechanisms are synchrotron radiation and the SSC process of the electrons accelerated in the shocks (e.g., Sari et al. 1998; Sari & Esin 2001). The distribution of the radiating electrons is taken as a single power-law function $dN/d\gamma_e \propto \gamma_e^{-p}$, where $\gamma_e$ is the electron Lorentz factor and $p$ is the electron spectral index. The synchrotron spectrum is characterized by several power-law segments with breaks at the synchrotron self-absorption frequency ($\nu_{sa}$), the photon frequency from the injected minimum-energy electrons ($\nu_{\gamma 0}$), and the cooling photon frequency $\nu_c$. In addition, the SSC component can be calculated by the synchrotron spectrum and the Compton parameter ($Y$ parameter) with break frequencies at $\nu_{IC}^c$, $\nu_m^c$, and $\nu_c^c$ (Panaitescu & Kumar 2000; Sari & Esin 2001).

The cross section for the IC scattering is suppressed when the photon energy in the electron rest frame exceeds $\sim m_e c^2$, which is the so-called Klein–Nishina (KN) effect. This effect is important at sufficiently high energies for GRB afterglows (Nakar et al. 2009; Wang et al. 2010). The Compton parameter $Y(\gamma_e)$ depends on the energy of electrons $\gamma_e$, which is given by the critical frequency of scattering

$$Y(\gamma_e) = \frac{U_{\text{syn}}[\nu < \nu_{\text{KN}}(\gamma_e)]}{U_{\text{B}}},$$

where $\nu_{\text{KN}}$ is the photons above which the scatterings with electrons of energy $\gamma_e$ enter the KN scattering regime, $U_{\text{syn}}[\nu < \nu_{\text{KN}}(\gamma_e)]$ is the energy density of the synchrotron photons with a frequency below $\nu_{\text{KN}}$, and $U_{\text{B}}$ is the energy density of the magnetic field.

The $Y(\gamma_e)$ parameter affects the electron radiative cooling function and modifies the electron distribution. The modified electron distribution in the fast-cooling case is given by

$$N(\gamma_e) = \frac{C_1 \gamma_e^{-2}}{1 + Y(\gamma_e)} \begin{cases} \gamma_m^{-1} \gamma_e^{-p}, & \gamma_m < \gamma_e < \gamma_m, \\ \gamma_e^{-p}, & \gamma_m < \gamma_e, \end{cases}$$

and in the slow-cooling case,

$$N(\gamma_e) = \begin{cases} C_2 \gamma_e^{-p}, & \gamma_m < \gamma_e < \gamma_c, \\ \frac{1}{1 + Y(\gamma_e)} C_2 \gamma_c \gamma_e^{-p-1}, & \gamma_c < \gamma_e, \end{cases}$$

where $\gamma_m$ is the minimum injection electron Lorentz factor and $\gamma_c$ is the Lorentz factor above which the electrons are cooled efficiently over the age of the system. $C_1$ and $C_2$ are constants. The resulting SED and light curves of the SSC components can then be obtained using this electron distribution. The approximate analytical forms of the SSC spectra in different spectral regimes are obtained in Nakar et al. (2009). It can be clearly seen that the KN effect affects the SSC spectrum significantly. In the present paper, we calculate the synchrotron and SSC spectra numerically, taking into account the KN effect.

We now calculate the broadband SEDs at $t = 100$ s and $t = 10$ hr after the burst and the light curves at 100 GeV for both types of media. The derived model parameter includes isotropic kinetic energy ($E_{k,\text{iso}}$), the energy partition factors of the electrons ($\epsilon_e$), the magnetic field ($\epsilon_B$), the initial Lorentz factor of the fireball ($\Gamma_0$), $n_0$, and $A_w$. We use the following reference parameter values: $E_{k,\text{iso}} = 1 \times 10^{53}$ erg, $\epsilon_e = 0.3$, $\epsilon_B = 1 \times 10^{-3}$, $\Gamma_0 = 2.4$, $\Gamma_0 = 300$, and $z = 0.4$. The number densities of the external medium are taken as $n_0 = 1 \text{ cm}^{-3}$ or $n_0 = 0.1 \text{ cm}^{-3}$ for the homogeneous medium and $A_w = 1$ or $A_w = 0.1$ for the wind medium case.

We first show the evolution of $\gamma_c$ and $\gamma_m$ as a function of time for two types of media in Figure 1 (left panel). For typical parameter values, the radiating electrons are in the slow-cooling regime in the homogeneous density case, while they are in the fast-cooling regime in the wind medium at an early time. The Compton parameters for electrons with $\gamma_c$ and $\gamma_m$ are shown in the right panel of Figure 1. For the slow-cooling case, $Y(\gamma_c)$ reflects roughly the flux ratio between the SSC component and the synchrotron component, while for the fast-cooling case, the ratio is roughly described by $Y(\gamma_m)$. In the homogeneous density medium (slow-cooling) case, a larger density leads to a larger $Y(\gamma_c)$. However, in the wind medium case, the Compton parameter (denoted by $Y(\gamma_m)$) is not sensitive to the density. In the wind medium case, the Compton parameter $Y(\gamma_m)$ increases to a value of about 10 for typical parameter values at an early time and then decreases quickly with time.

The SEDs of the SSC and synchrotron emissions are shown in Figure 2. It can be seen that the peak energy of the SSC emission is larger for a lower circum-burst density in both the homogeneous density medium and wind medium cases. This is

Figure 1. Left panel: the values of $\gamma_c$ and $\gamma_m$ as a function of time. The solid line and the dashed line represent the values of $\gamma_c$ and $\gamma_m$, respectively. The red and blue lines represent the case of the homogeneous medium with $n = 1 \text{ cm}^{-3}$ and $n = 0.1 \text{ cm}^{-3}$, respectively. Other parameter values used are $E_{k,\text{iso}} = 1 \times 10^{53}$ erg, $\epsilon_e = 0.3$, $\epsilon_B = 1 \times 10^{-3}$, $\rho = 2.4$, $\Gamma_0 = 300$, and $z = 0.4$. Right panel: Compton parameters $Y(\gamma_c)$ (solid lines) and $Y(\gamma_m)$ (dotted lines) as a function of time. The different color lines have the same meaning as that of the left panel.
due to lower density resulting in a larger $\gamma_c$ and $\gamma_m$ in both cases. The flux ratio between the SSC component and the synchrotron component follows the evolution of $Y(\gamma_c)$ for the slow-cooling case and $Y(\gamma_m)$ for the fast-cooling case. The ratio decreases more quickly with time in the wind medium case than in the homogeneous density medium case. These features can be used to distinguish the two types of media.

Figure 3 illustrates light curves at 100 GeV in the homogeneous density (left panel) and wind (right panel) medium cases. In the homogeneous density case, the SSC emission dominates over the synchrotron emission before tens of seconds after the burst. The SSC emission could be detectable by a Major Atmospheric Gamma Imaging Cerenkov Telescope (MAGIC) at $t < 1$ hours after the GRB trigger for the case of $n = 1$ cm$^{-3}$. For the wind case, the SSC component at 100 GeV dominates over the synchrotron component. The used parameter values are the same as those in Figure 1.

Figure 2. Broadband SEDs of GRB afterglows in the early stage ($t = 100$ s after the GRB trigger) and late stage ($t = 10$ hr after the GRB trigger) in the homogeneous medium with $n = 1$ cm$^{-3}$ and $n = 0.1$ cm$^{-3}$, and the wind medium with $A_\nu = 1$ and $A_\nu = 0.1$, respectively. Other parameter values used are $E_{k,\text{iso}} = 1 \times 10^{53}$ erg, $\epsilon_e = 0.3$, $\epsilon_B = 1 \times 10^{-3}$, $p = 2.4$, $\Gamma_0 = 300$, and $z = 0.4$. The yellow dashed lines represent the emission from the SSC process without considering the absorption in the source. The solid lines represent the sum of the emission from the synchrotron radiation (the dotted lines) and the absorbed radiation of the SSC component (the dashed lines).

Figure 3. Light curves of GRB afterglows at 100 GeV compared with the sensitivity of the MAGIC telescope in the homogeneous medium with $n = 1$ cm$^{-3}$ and $n = 0.1$ cm$^{-3}$ (left panel), and the wind medium with $A_\nu = 1$ and $A_\nu = 0.1$ (right panel), respectively. The gray dashed line represents the sensitivity curve of MAGIC at 100 GeV (Takahashi et al. 2008). The solid lines represent the sum of the emission from the synchrotron radiation (the dotted lines) and the absorbed radiation of the SSC component (the dashed lines).
synchrotron emission from the very beginning of the afterglow phase and the flux could be detectable for up to 1 hr after the GRB trigger in the case of \( A_\text{w} = 0.1 \). In the wind medium case, a plateau phase is clearly seen in the light curve at the early stage (<10\(^3\) s), which corresponds to the analytical result of \( F_\nu \propto (1 + Y_\gamma)^{-2} \frac{\nu^0}{\nu} \) in the frequency range \( \nu^{\text{IC}} < \nu < \nu^{\text{IC}} \), where \( \nu^{\text{IC}} \) is the optical depth of photons due to IC absorption in the source. Because the spectral regime of the observed frequency is different in the case of \( A_\text{w} = 1 \), the light curve of the SSC emission at 100 GeV is significantly lower, mostly due to a larger internal \( \gamma \gamma \) absorption in the source. The evolution of the light curve at 100 GeV is also different. Generally, the evolution of the light curve at 100 GeV is milder in the homogeneous density medium than in the wind medium case. These features can be used to distinguish the two types of media. The observed light curve of the sub-TeV emission from GRB 190114C agrees more with the homogeneous density case, as has been modeled in some previous works (MAGIC Collaboration et al. 2019; Wang et al. 2019, see also Fraija et al. 2019a).

3. Electromagnetic Cascade Emission of the Absorbed TeV Photons

3.1. The Cascade Process

The high-energy photons with energy \( \varepsilon_\gamma \) suffer from pair production absorption by the interaction of target photons with energy \( \varepsilon_\gamma \geq \sqrt{2m_e^2c^2\gamma^2}/\gamma \) in the source. Then a cascade process is induced and the energy of high-energy photons is redistributed into lower-energy photons, until the opacity of secondary photons becomes \( \tau_{\gamma\gamma} < 1 \). As an example, Figure 4 shows the opacity of a photon with 1 TeV of energy as a function of time.\(^6\) For the reference parameter values, the opacity in the homogeneous medium case is \( \tau_{\gamma\gamma} < 1 \) for 1 TeV photons from the beginning of the afterglow. However, the opacity is \( \tau_{\gamma\gamma} > 1 \) in the denser wind medium. This is due to the fact that a denser medium leads to a lower bulk Lorentz factor of the forward shock and hence a higher opacity for high-energy photons. Below we perform a comparative study of the cascade emission between homogeneous and wind media.

Following Böttcher et al. (2013), we adopt a semianalytical method to calculate the cascade emission for the purpose of an efficient calculation of cascades. We assume the high-energy photons of the SSC and synchrotron radiation, which are derived from the primary electron spectra (i.e., Equations (2) and (3)), to be the first-generation photon field. The injection rate of the first-generation photons is denoted by \( N_\gamma^0 \). Then the secondary high-energy photons are produced through synchrotron emission and IC processes, whose production rate is denoted by \( N_\gamma^{\text{sec}} \). Considering the absorption, the spectrum of escaping (observable) photons can be calculated as

\[
N_\gamma^{\text{esc}} = (N_\gamma^0 + N_\gamma^{\text{sec}}) \left( 1 - \frac{e^{-\tau_{\gamma\gamma}(\varepsilon)}}{\tau_{\gamma\gamma}(\varepsilon)} \right),
\]

(4)

where \( \tau_{\gamma\gamma}(\varepsilon) \) is the optical depth of photons due to \( \gamma \gamma \) absorption.

We then calculate the production rate of electron/positron pairs due to \( \gamma \gamma \) absorption. In the \( \gamma \gamma \) absorption of a high-energy photon of energy \( \varepsilon \), one of the produced particles takes the major fraction, \( f_{\gamma} \), of the photon energy. Hence, an electron/positron pair with energies \( \gamma_1 = f_{\gamma} \varepsilon \) and \( \gamma_2 = (1 - f_{\gamma}) \varepsilon \) is produced. Following Böttcher et al. (2013), we adopt \( f_{\gamma} = 0.9 \) in our calculation. Defining an absorption factor \( f_{\text{abs}}(\varepsilon) \) as

\[
f_{\text{abs}}(\varepsilon) = 1 - \frac{1 - e^{-\tau_{\gamma\gamma}(\varepsilon)}}{\tau_{\gamma\gamma}(\varepsilon)},
\]

(5)

the pair production rate can be written as

\[
N_\gamma^{\gamma\gamma}(\varepsilon) = f_{\text{abs}}(\varepsilon_1)(N_\gamma^0 + N_\gamma^{\text{sec}}) + f_{\text{abs}}(\varepsilon_2)(N_\gamma^0 + N_\gamma^{\text{sec}}),
\]

(6)

where \( \varepsilon_1 = \gamma_1/f_{\gamma} \) and \( \varepsilon_2 = \gamma_2/(1 - f_{\gamma}) \) (Böttcher et al. 2013; Veres et al. 2017).

The energy loss of electrons through synchrotron and SSC processes is given by

\[
\dot{\gamma}_e = \frac{4}{3} \frac{c \sigma_T}{m_e c^2} \gamma_e^2 f_{\text{KN}}(\gamma_e)[U_B + U_{\text{syn}} f_{\text{KN}}(\gamma_e)],
\]

(7)

where \( \sigma_T \) is the Thomson cross section, \( m_e \) is the electron mass, \( c \) is the light speed, and \( U_B \) and \( U_{\text{syn}} \) are, respectively, the energy density of the magnetic field and synchrotron photons. Here \( f_{\text{KN}} \) is a correction factor accounting for the KN effect, i.e., \( f_{\text{KN}}(\gamma_e) = f_{\text{min}} \exp(\ln \kappa - 11/6) \), where \( \kappa \) is the differential energy distribution of the synchrotron photons and \( \kappa = 4\gamma e^2 f_{\text{KN}} \) is approximated as (Moderski et al. 2005): \( f_{\text{KN}}(\kappa) \simeq \begin{cases} 1, & \kappa \ll 1 (\text{Thomson limit}) \\ 9 \frac{2\kappa}{\kappa^2 + 1}, & \kappa \gg 1 (\text{KN limit}) \end{cases} \)

(8)

In the calculation, we divide the time interval logarithmically. To achieve sufficient accuracy, we adopt a very small time increment \( \delta t = (10^{0.01} - 1) \) in the numerical calculation. The calculation of distribution of electron in the cascade at time \( t + \delta t \) can be divided into two parts. The first part is the cascade electrons accumulated from the beginning to time \( t \), the other

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\(^6\) We do not consider EBL absorption in the intergalactic space in our calculation.
part is the electrons newly produced in time from time \( t \) to \( t + \delta t \). For the accumulated electrons, the cooling effect can be included by considering the electron number conservation \( N_{e}^{\text{cool}}(\gamma_{e}, t + \delta t) d\gamma_{e} = N_{e}^{\text{sec}}(\gamma_{e}^{*}, t) d\gamma_{e}^{*} \), where \( \gamma_{e}^{*} \) is the electron Lorentz factor at time \( t \) and, due to the cooling effect, the Lorentz factor will decrease from \( \gamma_{e}^{*} \) to \( \gamma_{e} \) during the time interval \( \delta t \). For the newly produced electrons in time interval \( \delta t \), the calculation is divided into two cases according to the relation between the cooling timescale of electrons and the time interval. When the electron cooling timescale is less than the time interval (i.e., \( \tau_{e}^{\text{cool}}(\gamma_{e}) < \delta t \)), the cascade process tends to be in a quasi-steady state and the electron distribution is given by Böttcher et al. (2013)

\[
N_{e}^{\text{sec}}(\gamma_{e}, t + \delta t) = N_{e}^{\text{sec}}(\gamma_{e}^{*}, t) \frac{d\gamma_{e}^{*}}{d\gamma_{e}} + \frac{1}{\gamma_{e}} \int_{\gamma_{e}^{*}}^{\infty} d\gamma_{e}^{*} N_{e}^{\gamma}(\gamma_{e}, t + \delta t). \tag{9}
\]

While, for the case of \( \tau_{e}^{\text{cool}}(\gamma_{e}) > \delta t \), the electron distribution is given by

\[
N_{e}^{\text{sec}}(\gamma_{e}, t + \delta t) = N_{e}^{\text{sec}}(\gamma_{e}^{*}, t) \frac{d\gamma_{e}^{*}}{d\gamma_{e}} + N_{e}^{\gamma}(\gamma_{e}, t + \delta t) \delta t. \tag{10}
\]

### 3.2. The Cascade Emission in Homogeneous and Wind Media

Taking the cascade emission into account, we recalculate the SEDs and the light curves of the afterglows with the same parameter set, as mentioned above. Figure 5 illustrates the broadband SEDs of the afterglows at \( t = 100 \text{ s} \) and \( t = 10 \text{ hr} \) in homogeneous and wind media with number densities of \( n_{0} = 1 \text{ cm}^{-3} \) and \( A_{w} = 1 \), respectively.

For the case of \( n_{0} = 1 \text{ cm}^{-3} \) at \( t = 100 \text{ s} \) (the upper left panel of Figure 5), the cascade synchrotron component at \( \sim 1 \text{ eV} \) and the cascade SSC emission at \( \sim 100 \text{ GeV} \) are both comparable to that of the primary electron population (the cascade emission is marked as a black solid line). In the cases of \( n_{0} = 1 \text{ cm}^{-3} \) at \( t = 10 \text{ hr} \), the broadband SEDs are overwhelmingly dominated by the radiation from the primary syn+SSC electron population. In the wind medium, the cascade emission is also sensitive to \( A_{w} \). The cascade radiation contributes significantly to the whole SED for \( A_{w} = 1 \) at the early stage \( (t = 100 \text{ s}) \). The cascade SSC emission contributes significantly to the left shoulder of the SSC bump. On the other hand, the cascade synchrotron emission dominates the optical flux (\( \sim 1 \text{ eV} \)). At the late epoch of \( t = 10 \text{ hr} \), the cascade emission only contributes weakly to the SED around \( \sim 10^{4} \text{ eV} \), and is ignorable in other bands in comparison with the emission from the primary electron population.

Figure 6 shows the corresponding monofrequency light curves in homogeneous and wind media with number densities
Figure 6. Light curves of GRB afterglows in several energy bands (1 eV, 1 keV, 1 MeV, and 1 GeV) in the homogeneous medium with a number density of \(n = 1 \text{ cm}^{-3}\) (left panels) and the wind medium with a number density of \(A_\star = 1\) (right panels). The black solid lines represent the sum of the emission from the synchrotron emission, SSC emission, and cascade emission. The red solid lines represent the sum of the emission from the synchrotron emission and the SSC emission after considering the \(\gamma\gamma\) absorption. The green solid lines represent the sum of the cascade emission from the synchrotron emission and SSC emission of the secondary electrons produced during pair production. The parameter values used are the same as those in Figure 1. Note that the spikes in some plots arise from the discontinuity of the KN factors that are obtained approximately in our calculation during the transition between the fast-cooling and slow-cooling cases.
of $n_0 = 1 \text{ cm}^{-3}$ and $A_\nu = 1$, respectively. For the homogeneous medium, the extra cascade emission component shows up mainly in the optical ($\sim 1 \text{ eV}$) light curves. The superimposed effect of the emission from both the primary and cascade electrons flattens the light curves at the early stage. This might explain the plateau seen in the early optical afterglows of some GRBs (e.g., Panaitescu & Vestrand 2011; Liang et al. 2013). The cascade emission contributes subdominantly to the X-ray afterglow for typical parameter values. It may lead to a plateau in X-rays at an early time if the density of the circum-burst medium is sufficiently high. Some GRBs also display a plateau in X-rays at late times (Fraija et al. 2019a, 2020), which is, however, hard to explain with the cascade emission. The monofrequency light curves in the wind medium are different from those in the homogeneous medium. The light-curve behaviors depend on the competition between the primary and cascade radiation. At the early stages ($t \lesssim 1000 \text{ s}$), the light curves are dominated by the cascade emission, while they are dominated by the primary SSC emission at a late stage. The overlapped effect of the primary and cascade radiation makes the light curves complicated, but they generally illustrate a shallow decay followed by a steep decay segment.

4. Conclusions and Discussion

We have presented a comparative analysis of the sub-TeV emission of GRB afterglows in homogeneous and wind media in the framework of synchrotron and SSC emissions of electrons accelerated in forward shock. The attenuation of very-high-energy photons in the source due to $\gamma\gamma$ absorption and the KN effect on the SSC spectrum are considered. We find that the flux of the SSC emission could be detectable with current Imaging Atmospheric Cerenkov Telescopes up to $\sim 10 \text{ hr}$ after the GRB trigger for GRB 190114C-like bright GRBs in an ISM medium with a number density of $n \sim 1 \text{ cm}^{-3}$ or in the wind medium with $A_\nu \sim 0.1$. Generally, the SSC emission is stronger in the denser environment. But a too dense medium, e.g., a wind medium with $A_\nu = 1$, will suppress the sub-TeV emission due to the severe $\gamma\gamma$ absorption. For future telescopes, such as the Cerenkov Telescope Array, the detection rate of sub-TeV emission from GRBs would be increased significantly. The light curves of the sub-TeV emission are different for the two types of media, which can be used to distinguish the circum-burst medium in the future.

The absorbed high-energy photons lead to cascade emission at low energies. In the homogeneous ISM scenario, the cascade emission could be comparable to the synchrotron of the primary electrons in the optical band and flatten the early optical afterglow light curve ($t \lesssim 1 \text{ hr}$). In the wind medium, the cascade emission at an early time is comparable to or even larger than the emission of the primary electrons in a wide range of frequencies. It has been found that the observed diversity of the early optical light curves is hard to explain in the simple external shock model (e.g., Wang et al. 2015). The cascade mission might be helpful to explain this diverse behavior of the optical afterglows, as well as X-ray afterglows.

A detailed study of this possibility is, however, beyond the scope of the present paper.

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