LUMINOUS SUPERNOVA-LIKE UV/OPTICAL/INFRARED TRANSIENTS ASSOCIATED WITH ULTRA-LONG GAMMA-RAY BURSTS FROM METAL-POOR BLUE SUPERGIANTS

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ABSTRACT

Metal-poor massive stars typically end their lives as blue supergiants (BSGs). Gamma-ray bursts (GRBs) from such progenitors could have an ultra-long duration of relativistic jets. For example, Population III (Pop III) GRBs at $z \sim 10–20$ might be observable as X-ray-rich events with a typical duration of $T_{90}$ $\sim 10^4(1 + z)$ s. The recent GRB111209A at $z = 0.677$ has an ultra-long duration of $T_{90} \sim 2.5 \times 10^3$ s and it has been suggested that its progenitor might have been a metal-poor BSG in the local universe. Here, we suggest that luminous UV/optical/infrared emission is associated with this new class of GRBs from metal-poor BSGs. Before the jet head breaks out of the progenitor envelope, the energy injected by the jet is stored in a hot plasma cocoon, which finally emerges and expands as a baryon-loaded envelope. We show that the photospheric emissions from the cocoon fireball could be intrinsically very bright ($L_{\mathrm{peak}} \sim 10^{42}–10^{44}$ erg s$^{-1}$) in UV/optical bands ($\epsilon_{\mathrm{peak}} \sim 10$ eV) with a typical duration of $\sim 100$ days in the rest frame. Such cocoons from Pop III GRBs might be detectable in infrared bands at $\sim$ years after Pop III GRBs at up to $z \sim 15$ by upcoming facilities such as the James Webb Space Telescope. We also suggest that GRB111209A might have been rebrightening in UV/optical bands up to an AB magnitude of $\lesssim 26$. The cocoon emission from local metal-poor BSGs might have been observed previously as luminous supernovae without GRBs since they can be seen from the off-axis direction of the jet.

Key words: gamma-ray burst: general – infrared: general – stars: Population III

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1. INTRODUCTION

Direct signals from Population III (Pop III) stars are needed to confirm their existence as well as to know the earliest history of star formation, galaxy evolution, and cosmic reionization at $z \gtrsim 10$. However, observing Pop III stars in their stellar phase is extremely difficult due to their distance from Earth. Therefore, the core-collapse phase may be more suitable for observing Pop III stars. Possible supernovae (SNe) and gamma-ray bursts (GRBs) by Pop III stars are particularly good candidates for such observations.

Pop III stars are believed to form in dark-matter halos of $\sim 10^6 M_\odot$ at $z \gtrsim 20$. Molecular hydrogen can cool gas to $\sim 200$ K, prompting onset of the Jeans instability which forms gas clumps of $\sim 10^3 M_\odot$ (e.g., Bromm et al. 1999; Nakamura & Umemura 2002). If the most mass possible is accreted to form the star, a Pop III star at the zero-age main sequence (ZAMS) would be as massive as $M_{\mathrm{ZAMS}} \sim 10^2–10^3 M_\odot$. If this is the case, then Pop III stars with ZAMS masses in the range $140–260 M_\odot$ would result in pair-instability supernovae (PISNe; Woosley et al. 2002). Detailed numerical simulations have shown that the signals of PISNe can be detected in infrared bands up to $z \sim 30$ using the James Webb Space Telescope (JWST; e.g., Whalen et al. 2013). As for even more massive stars, several core-collapse simulations have been performed, which produced black holes (BHs) with $M \sim 10^2(100) M_\odot$ (e.g., Fryer et al. 2001; Suwa et al. 2007a, 2007b).

However, such large ZAMS mass Pop III stars seem to form only in spherically symmetric systems so that the ZAMS mass of Pop III stars may change when we take the effects of rotation into account. Some cosmological simulations indicate that the rotation of these gas clumps can naturally split them into subclumps of $\lesssim 100 M_\odot$ (Turk et al. 2009; Stacy et al. 2010; Clark et al. 2011). Even if the seed gas clump is more massive, the protostellar UV radiation evaporates a significant fraction of the mass so that the Pop III stars are as small as $M_{\mathrm{ZAMS}} \lesssim (30–90) M_\odot$ (McKee & Tan 2008; Hosokawa et al. 2011). Population III 2 stars, which may be more abundant than other Pop III stars, can also have smaller ZAMS masses (e.g., Yoshida et al. 2007). Massive Pop III stars typically end their lives as blue supergiants (BSGs) with massive hydrogen envelopes due to the low opacity in their envelopes (Woosley et al. 2002).

Several authors have discussed the possibility of GRBs as markers of such BSG Pop III stars (Mészáros & Rees 2010; Komissarov & Barkov 2010; Suwa & Ioka 2011; Nagakura et al. 2012; Woosley & Heger 2012); we will discuss this subject further in a later section. One of the most promising scenarios for long GRBs is the collapsar model in which relativistic jets burrowing through the stellar envelope are indispensable for bringing relativistically moving elements into an optically thin region without dissipation. For massive progenitors with sufficient angular momentum, a stellar mass BH with an accretion disk would first be formed in the core-collapse phase (Woosley 1993; Narayan et al. 2001), and relativistic jets may be launched via the Blandford–Znajek (BZ) or similar process (Blandford & Znajek 1977; McKinney & Gammie 2006).
If the jet can break out of the stellar envelope before the central engine ceases, it may produce prompt gamma rays via dissipation processes near and beyond the photospheric radius (see, e.g., Mészáros 2013). Also, one can expect radio to infrared afterglows via synchrotron emissions from the non-thermal electrons accelerated at the shocks in the relativistic shell going through the circumstellar medium (Ioka & Mészáros 2005; Inoue et al. 2007; Toma et al. 2011; Nakauri et al. 2012).

The large pre-collapse mass expected for Pop III stars was thought to be problematic for a scenario where the jet breaks out of the envelope. Indeed, Matzner (2003) claimed that the progenitors of observed long GRBs would not be giant stars like red supergiants but compact stars like CO Wolf–Rayet (WR) stars. Nevertheless, several authors have claimed that Pop III stars can produce GRBs irrespective of their pre-collapse masses (Mészáros & Rees 2010; Suwa & Ioka 2011; Nakagura et al. 2012; Woosley & Heger 2012), essentially because they would be BSGs in the pre-collapse phase (Mészáros & Rees 2001).

A large mass would afford a larger intrinsic energy budget, and the relative compactness of the large mass would help the jet to reach the stellar edge before the engine ceased. As an interesting outcome, the duration of the prompt emission of Pop III or BSG GRBs would be much longer than the observed values (Suwa & Ioka 2011; Nakauri et al. 2012). Nakauri et al. (2012) doubted the detectability of such ultra-long GRBs from BSGs and found that if the peak spectral energy is less than the observed spectral energy and isotropic equivalent energy (E_p - E_{iso}) holds, the observed E_{obs} \sim 100 keV with E_{iso} \sim 10^{54} erg and duration \tau_{obs} = 6 \times 10^{4} s for a Pop III BSG with a mass of 40 M_\odot at z = 9 which can be detected by future instruments such as the Energetic X-ray Imaging Survey Telescope (EXIST). These values are similar to the recent observation of the ultra-long GRB111209A with E_{iso} = 5.82 \times 10^{53} erg, E_{obs} = 310 keV, and a duration of \sim 2.5 \times 10^{4} s (Gendre et al. 2013). Given that the observed redshift is relatively small, z = 0.677, the progenitor of this GRB might be a metal-poor BSG in the local universe.

Here, we propose a new possible photon emission associated with such ultra-long GRBs from Pop III stars or more general BSG progenitors. We consider a cocoon, i.e., a hot plasma sheath of the jet, which is a necessary ingredient of the above-mentioned collapsar model of GRBs. Before the jet breaks out of the progenitor, the energy is stored in the cocoon (e.g., Lazzati & Begelman 2005; Bromberg et al. 2011), which finally emerges and expands as a baryon-loaded fireball. We evaluate phosforphoric emission from such cocoon fireballs for various progenitors and discuss the detectability of such emission. We show that the emission is sensitive to the progenitor, so the cocoon-fireball photospheric emission (hereafter CFPE) can be a diagnostic indicator of Pop III and BSG GRBs.

This paper is organized as follows. In Section 2, we introduce GRB progenitor models which we use in the following calculations. In Section 3, we model jet-cocoon formation and evolution before and after breaking out each progenitor. In Section 4, we model CFPE, and evaluate the detectability. In Section 5, we summarize our calculations.

2. PROGENITOR MODEL

We consider massive stars (M_{ZAMS} \geq 40 M_\odot) with zero (Z = 0), low (Z = 10^{-4} Z_\odot), and solar metallicity (Z = Z_\odot). We use pre-collapse stellar models from Woosley et al. (2002), Heger & Woosley (2010), and Ohkubo et al. (2009), which are given in Table 1. The first column shows model names which include a letter representing metallicity (z: zero; l: low; s: solar), the ZAMS mass, and the pre-collapse state (BSG or WR). The mass (M_\ast) and the radius (R_\ast) in the pre-collapse phase are shown in the second and third columns, respectively. One can see that only the progenitors with solar metallicity lose their dominant masses before collapsing to become WR stars. This is due to the strong stellar wind blowing out of the hydrogen envelope, which may not be present in zero- or low-metal stars due to the low opacity in their envelope. Such mass loss also makes the WR progenitors much more compact than the BSG progenitors.

3. COCOON FORMATION AND EVOLUTION

3.1. Before Jet-cocoon Breakouts

In the case of massive progenitors with a pre-collapse mass \geq 40 M_\odot, a stellar mass BH would first form just after the collapse is triggered (Heger et al. 2003). We assume that the initial BH mass is 3 M_\odot, and evaluate the time-dependent mass accretion onto the BH as

$$M(t) = \alpha \frac{dM_r}{dt}|_{t=t_\text{ff}(t)}. \quad (1)$$

Here, M_r = \int_0^r 4\pi \rho_s(r')^2 r' dr' is the mass coordinate for M_r > 3 M_\odot with \rho_s(r) being the density of the stellar envelope. t_\text{ff} = (r^3/GM_r)^{1/2} is the free-fall time of a mass shell dM_r with G being the gravitational constant, and \alpha [1] represents the deviation from the free-fall accretion, which may be time-dependent (see, e.g., Kumar et al. 2008). We use t as a time coordinate from the start of the accretion in the rest frame of the central engine.

We assume that the luminosity of the relativistic jet is proportional to the mass accretion rate onto the central BH:

$$L_j(t) = \eta_j M(t) c^2, \quad (2)$$

where \eta_j is the efficiency factor and c is the speed of light. Equation (2) can be realized in the BZ-like process (e.g., Komissarov & Barkov 2010; Kawana et al. 2013). Note that \eta_j may also be time-dependent.

When the jet collides with the stellar envelope, two shocks are formed: a forward shock propagating in the stellar envelope and a reverse shock in the jet. We call the region sandwiched between these two shocks the cocoon. We evaluate photospheric emission from such cocoon fireballs for various progenitors and discuss the detectability of such emission. We show that the emission is sensitive to the progenitor, so the cocoon-fireball photospheric emission (hereafter CFPE) can be a diagnostic indicator of Pop III and BSG GRBs.

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7 Another alternative possibility for the jet production mechanism is the neutrino process (MacFadyen & Woosley 1999; Popham et al. 1999; Zalamea & Beloborodov 2011; Suwa 2012) in which copious amounts of neutrinos and anti-neutrinos emitted from the hyperaccreting disk annihilate in the vicinity of the axis and produce a fireball consisting of hot electron–positron pairs.

8 In Suwa & Ioka (2011) and Nakauri et al. (2012), the suppression factor of the accretion rate, \alpha, was absorbed in the definition of the jet efficiency \eta_j. Their \eta_j corresponds to \eta_j in this paper.

9 The sufficient condition is \hat{L}(t) \ll \Gamma_j^4.
where
\[ \dot{L}(t) = \frac{L_0}{\tau_{\text{bo}}^2 r_h^2 \rho_c(r_h) c}, \]
and \( \theta_j \) is the half-opening angle of the jet. Here, the subscripts “j” and “h” refer to the jet and the jet head, respectively. The position of the jet head is obtained from \( r_h = r_0 \int_0^t \rho_c dt \).

If the jet head is non-relativistic, \( \rho_c \lesssim 0.3 \), a dominant fraction of shocked plasma there will spread out sideways to form a cocoon (e.g., Bromberg et al. 2011). The energy stored in the cocoon is evaluated as
\[ E_c(t) = \int_0^t \frac{\dot{L}(t) - r_h(t)}{\rho_c(r_h) c^2} dt'. \]

The pressure balance at the cocoon–progenitor interface, \( E_c/3V_c = \rho_c \beta_c^2 c^2 \), yields the transverse expansion velocity of the cocoon as
\[ \beta_c(t) = \left( \frac{E_c(t)}{3 \rho_c(r_h) c V_c(t)} \right)^{1/2}. \]

The transverse size of the cocoon is given by \( r_c = r_0 \int_0^t \beta_c dt \).

Finally, one can evaluate the baryon mass loaded in the cocoon as
\[ M_c(t) = \frac{r_c(t)^2}{4 \rho_c(r_c)} \int_0^t 4 \pi r^2 \rho_c(r) dr. \]

In principle, the cocoon is divided into an inner cocoon consisting of the shocked-jet matter and an outer cocoon of the shocked stellar matter. The two regions can be separated by a contact discontinuity (e.g., Bromberg et al. 2011). In Equation (8), we assume that the contact surface becomes unstable due to, e.g., a Kelvin–Helmholtz-type instability, and the outer inner cocoon are fully mixed. We discuss the cases where such cocoon mixing is insufficient in Section 5.

If the jet head arrives at the stellar surface before the central engine ceases, that is, \( t_{\text{bo}} < t_{\text{ff}}(R_*/\alpha) \), the jet succeeds in breaking out of the stellar envelope, where \( t_{\text{bo}} \) is defined by \( r_h(t_{\text{bo}}) = R_* \). Hereafter the subscript “bo” stands for breakout. Note that the jet can successfully break out of the stellar envelope for all the progenitor models shown in Table 1.

In our prescription, the three parameters \( \alpha, \eta_j \), and \( \theta_j \) determine whether or not the jet breaks out of the envelope and they determine the parameters of the cocoon. In general, both \( \alpha \) and \( \eta_j \) depend on time due to the details of the accretion disk formation and the magnetic field structure around the BH. The jet opening angle \( \theta_j \) also depends on time due to compression from the cocoon pressure (e.g., Lazzati & Begelman 2005; Bromberg et al. 2011). In the following calculation, we use \( \alpha = 1, \eta_j = 6.2 \times 10^{-4} \), and \( \theta_j = 0.1 \) as fiducial values. By applying these values to WR progenitors, we show that the observed characteristics of canonical GRBs can be reproduced (Suwa & Ioka 2011).

Figure 1 shows the mass accretion rate in the central-engine rest frame of each progenitor model in Table 1. The dotted and solid regions correspond to the time before and after the jets break out of the progenitors, respectively. One can see that metal-poor progenitors share some characteristics. Their accretion rate is initially as high as \( \sim 1-100 M_\odot \text{s}^{-1} \), and it suddenly decreases by \( \sim 10^{-2} \) at \( t \sim 10 \text{s} \). This transition corresponds to the end of the accretion of the He core. After that, the accretion rate shallowly decreases as approximately \( \alpha \approx 0.73 \) when the hydrogen envelope is accreted (Suwa & Ioka 2011). The jet typically breaks out of the envelope at \( t \sim 10 \text{s} \). Even at this time, the accretion rate is still \( \gtrsim 10^{-3} M_\odot \text{s}^{-1} \) which may sustain the relativistic jet activity (Chen & Beloborodov 2007; Kawanaka et al. 2013). The accretion essentially ends at \( t \gtrsim 10^3 \text{s} \), which is consistent with the observed duration of ultra-long GRBs. On the other hand, in the case of a WR progenitor, the jet breakout occurs at \( t \lesssim 10 \text{s} \), and the massive accretion ends at \( t \sim 10^3 \text{s} \). This is consistent with the observed duration of typical long GRBs.

### Table 1

| Progenitor Model | \( M_\odot \) (\( M_\odot \)) | \( R_* \) (cm) | \( (\alpha, \eta_j, \theta_j) \) | \( E_{c,\text{bo}} \) (erg) | \( V_{c,\text{bo}} \) (\( c M_\odot \)) | \( M_{c,\text{bo}} \) (\( M_\odot \)) | \( t_{c,\text{bo}} \) (days) | \( L_{\text{peak}} \) (erg \( \text{s}^{-1} \)) | \( t_{\text{peak}} \) (days) |
|------------------|-----------------|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| z40BSG(1)        | 40              | 1.5 \times 10^{12} | Fiducial       | 1.8 \times 10^{32} | 3.2 \times 10^{25} | 0.92             | 3.4 \times 10^6 | 0.011           | 2.4 \times 10^{32} | 13              | 87              |
| z70BSG(2)        | 70              | 1.4 \times 10^{12} |                | 3.9 \times 10^{32} | 1.5 \times 10^{28} | 0.88             | 6.7 \times 10^7 | 0.025           | 1.0 \times 10^{33} | 11              | 94              |
| z915BSG(3)       | 915             | 8.8 \times 10^{12} |                | 6.2 \times 10^{32} | 5.0 \times 10^{27} | 1.6              | 2.2 \times 10^8 | 0.022           | 2.1 \times 10^{35} | 9.5              | 350             |
| z600BSG(4)       | 40              | 4.4 \times 10^{12} |                | 1.8 \times 10^{32} | 1.0 \times 10^{27} | 1.1              | 3.9 \times 10^8 | 0.001           | 4.8 \times 10^{32} | 12              | 91              |
| r75BSG(5)        | 75              | 8.6 \times 10^{12} |                | 4.5 \times 10^{32} | 7.5 \times 10^{27} | 2.1              | 1.9 \times 10^6 | 0.012           | 1.2 \times 10^{33} | 11              | 120             |
| s40WR(6)         | 8.7             | 2.3 \times 10^{10} |                | 2.3 \times 10^{31} | 6.5 \times 10^{29} | 0.11             | 3.1 \times 10^5 | 0.012           | 6.8 \times 10^{30} | 22              | 40              |
| s75WR(7)         | 6.3             | 3.7 \times 10^{10} |                | 1.1 \times 10^{31} | 2.5 \times 10^{30} | 0.075            | 8.9 \times 10^4 | 8.0 \times 10^3 | 5.5 \times 10^{30} | 21              | 37              |

Notes. Column 1 shows model names which include a letter representing metallicity (z: zero; l: low; s: solar), the ZAMS mass, and the pre-collapse state (BSG or WR). Columns 2 and 3 show the mass and the radius of the progenitors, respectively. Column 4 shows the parameter of our theoretical model. Fiducial parameter means \((\alpha, \eta_j, \theta_j) = (1, 6.2 \times 10^{-4}, 0.1)\). Columns 5–12 show the energy, the volume, the mass, and the optical depth of the cocoon at jet breakout, the baryon load parameter, the peak luminosity, the peak energy, and the peak time of cocoon-fireball photospheric emission (CFPE), respectively.

For details, see the text.

References. (1) Woosley et al. 2002; (2) Heger & Woosley 2010; (3) Ohkubo et al. 2009.
In Table 1, the internal energy \(E_{c,bo} \equiv E_{c}(t_{bo})\), volume \((V_{c,bo} \equiv V_{c}(t_{bo}))\), and baryon mass of the cocoon \((M_{c,bo} \equiv M_{c}(t_{bo}))\) at the jet-cocoon breakout are shown for various progenitors. We also show the so-called baryon-load parameter of the cocoon, \[ \eta_c \equiv \frac{E_{c,bo}}{M_{c,bo} c^2}, \] and the optical depth of the cocoon at the breakout, \[ \tau_{c,bo} = \frac{\sigma_T M_{c,bo} R_c}{m_p V_{c,bo}}. \] Here \(\sigma_T = 6.7 \times 10^{-25} \text{ cm}^2\) is the Thomson cross section and \(m_p\) is the proton mass. We should note that the cocoon is all non-relativistic,\(^{10}\) i.e., \(\eta_c < 1\), and also the cocoon fireballs are highly optically thick at the breakout, i.e., \(\tau_{c,bo} \gg 1\).

### 3.2. After Jet-cocoon Breakouts

As shown below, the evolution of the cocoon after the jet-cocoon breaks out of the progenitor can be characterized by \((R_s, E_{c,bo}, M_{c,bo}, V_{c,bo}).\) For simplicity we do not consider an additional energy injection into the cocoon from the jet after the breakout.

The temperature of the cocoon fireball at breakout can be determined from \(E_{c,bo} = a T_{c,bo}^4 V_{c,bo} + M_{c,bo} k_B T_{c,bo}/m_p\) in the case of a cocoon fireball, the first term on the right-hand side is always dominant, i.e., the fireball is radiation-dominated, where the temperature evolution is described as \(T_c = T_{c,bo} (V_c/V_{c,bo})^{-3/4}\) with \[ T_{c,bo} = \left( \frac{E_{c,bo}}{a V_{c,bo}} \right)^{1/4}. \] Here \(a = 7.6 \times 10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4}\) and \(k_B = 1.4 \times 10^{-16} \text{ erg K}^{-1}\) are the radiation constant and the Boltzmann constant, respectively. The radiation energy evolves as \(a T_{c}^4 V_c \propto (V_c/V_{c,bo})^{-1/3}\), and the gas energy evolves as \((M_{c,bo}/m_p) k_B T_c \propto (V_c/V_{c,bo})^{-1/3}\). Since the scaling is the same, if the radiation dominates initially, the situation will remain if the cocoon is optically thick.

First, the fireball would expand in an almost spherically symmetric manner, and the volume and the optical depth evolve as \(V_c = V_{c,bo} (R/R_s)^3\), \(\tau_c = \pi M_{c,bo} R/m_p V_c = \tau_{c,bo} (R/R_s)^{-2}\), where \(R\) is the radius of the fireball. As long as the cocoon is optically thick, the kinetic energy \(K_c\) increases with the volume as \(d K_c \approx p_c dV_c \approx a T_c^4 dV_c/3 = a T_{c,bo}^4 V_{c,bo} (R/R_s)^{-2} d(R/R_s)\), which gives \(K_c(R) = E_{c,bo}\left(1 - (R/R_s)^{-2}\right)\). This means that once the cocoon fireball expands to twice as large as its initial size, \(R_{sat} \approx 2 R_s\).

\[ R_{sat} \approx 2 R_s, \] a considerable fraction of the internal energy will be transferred to kinetic energy. The saturation velocity of the cocoon fireball is \(v_{sat} \approx (2 E_{c,bo}/M_{c,bo})^{1/2} = \sqrt{2 \eta_c c}\). The fluctuation of the velocity within the fireball \(\delta v \approx (k_B T_c/m_p)^{1/2} < (k_B T_{c,bo}/2 m_p)^{1/2}\) is always much smaller than \(v_{sat}\). \(\delta v/v_{sat} < (M_{c,bo} k_B T_{c,bo}/m_p E_{c,bo})^{1/2} \ll 1\). Thus, the cocoon fireball can be approximated as a shell with a width \(\Delta R \approx R_{sat}\) beyond the saturation radius, where the volume and the temperature evolve as \(V_c \propto (R/R_{sat})^3\) and \(T_c \propto (R/R_{sat})^{-2}\), respectively. The optical depth still evolves as \(\tau_c = \tau_{c,bo}(R/R_s)^{-2}\). Finally, the diffusion velocity of photons within the shell becomes equal to the coasting velocity of the shell, i.e., \(c/\tau_c \approx v_{sat}\). This occurs at the photospheric radius given by
\[ R_{ph} \approx 1.2 R_s \times (\tau_{c,bo}^2 \eta_c)^{1/4}. \]

In summary, cocoon fireballs evolve as
\[ V_c = V_{c,bo} \begin{cases} \left( \frac{R}{R_s} \right)^{-3} & (R_s < R < R_{sat}) \\ \left( \frac{R_{sat}}{R_s} \right)^{-3} \left( \frac{R}{R_{sat}} \right)^{-2} & (R_{sat} < R < R_{ph}) \end{cases} \]
\[ T_c = T_{c,bo} \begin{cases} \left( \frac{R}{R_s} \right)^{-1} & (R_s < R < R_{sat}) \\ \left( \frac{R_{sat}}{R_s} \right)^{-1} \left( \frac{R}{R_{sat}} \right)^{-2/3} & (R_{sat} < R < R_{ph}) \end{cases} \]
\[ \tau_c = \tau_{c,bo} \left( \frac{R}{R_s} \right)^{-2}. \]

### 4. COCONN-FIREBALL PHOTOSPHERIC EMISSION

In this section, we evaluate the photon emission from the cocoon fireball. Here we only consider thermal photons and neglect other photon injection processes, e.g., the electron-synchrotron process, and bremsstrahlung emission, which would have a minor contribution in the cases we study. Also we neglect gamma rays as a decay product of unstable nuclei like \(^{56}\)Ni. In fact, Tomimaga et al. (2007) showed that the abundance of \(^{56}\)Ni synthesized by relativistic jets would be small. Moreover, we neglect the effect of absorptions by nuclei included inside the fireball for simplicity.

In the coasting phase, thermal photons within a width of \(\approx \Delta R c/\tau_c v_{sat}\) can escape the shell since they have a larger diffusion velocity than the coasting velocity of the shell. For
a fixed radius $R$, the radiation first comes from near the line of sight and later from the limb so that the photons from the fixed $R$ are observed with a duration $\approx R/v_{\text{sat}}$. Then, the mean bolometric luminosity can be evaluated as $L_b \approx a T^4 \times 4\pi R^2(\Delta \rho c/\tau_{\text{sat}}) \times (R/v_{\text{sat}})^{-1} \propto (R/R_{\text{sat}})^{1/3} \propto t^{1/3}$, which becomes the maximum at the photospheric radius, $R \approx R_{\phi}$. The timescale of the emission is estimated to be $t_{\text{peak}} \approx R_{\phi}/v_{\text{sat}}$

$$t_{\text{peak}} = 0.84(R_c/c) \times (\tau_{c,\text{bo}}^2/\eta_c)^{1/4}. \quad (17)$$

The peak bolometric luminosity is described as $L_{\text{peak}} \approx E_{\text{c,bo}} \times (R_{\text{sat}}/R_c)^{-1}(R_{\phi}/R_{\text{sat}})^{-2/3} \times t_{\text{peak}}^{-1}$, or

$$L_{\text{peak}} = 0.84(E_{\text{c,bo}}/c) \times \tau_{c,\text{bo}}^{-5/6} \eta_c^{1/12} \phantom{} 1/2, \quad (18)$$

and the peak photon energy is $\varepsilon_{\text{peak}} \approx 3.92k_B T_{c,\text{bo}} \times (R_{\text{sat}}/R_c)^{-1}(R_{\phi}/R_{\text{sat}})^{-2/3}$, or

$$\varepsilon_{\text{peak}} = 2.8k_B T_{c,\text{bo}} \times (\tau_{c,\text{bo}}^2/\eta_c)^{-1/6}. \quad (19)$$

In Table 1, we show $(L_{\text{peak}}, \varepsilon_{\text{peak}}, t_{\text{peak}})$ for each progenitor.

Figure 2 shows intrinsic bolometric luminosities of CFPEs. We simply assume an exponential cutoff at $t = t_{\text{peak}}$ for each case. This treatment would be justified since Pe'er et al. (2006) numerically show that the cutoff is steeper than $\alpha t^{-4}$ for relativistic cocoon fireballs. The initial energy stored in the cocoon for $z70BSG$ is about two times larger than that for $z40BSG$, while the initial optical depth and the baryon load of $z70BSG$ are smaller than that of $z40BSG$ (see Table 1). Then, the cocoon of $z70BSG$ becomes transparent much faster than that of $z40BSG$ so that $z70BSG$ is brighter. The initial optical depth for $z915BSG$ is $\sim$30 times larger than that of $z70BSG$ while the baryon load $\eta_c$ is similar for both BSGs. Both the initial cocoon energy and the baryon mass of $z915BSG$ are larger than those of $z70BSG$. As a result, the evolution of the fireball looks similar for both BSGs, but the duration in $z70BSG$ becomes shorter.

Comparing progenitors with different metallicities, the CFPE from metal-poor BSG progenitors with $Z = 10^{-4} Z_\odot$ is similar to that of Pop III progenitors, which can be understood from the fact that their pre-collapse stellar structures are also similar. In contrast, the cocoon emission from the WR progenitors is much dimmer than that of other progenitors. This is essentially because the timescale for the jet to break out of the envelope is much shorter in the case of WR progenitors so that the energy stored in the cocoon is relatively small, about a tenth of that for $zBSG40$. As a result, the peak luminosity is $\lesssim 100$ times dimmer. Therefore, the observation of the CFPE can be used as a diagnostic tool for determining successful Pop III GRBs and BSG GRBs. Moreover, in principle, one could constrain the progenitor mass from the observed parameters, $(L_{\text{peak}}, \varepsilon_{\text{peak}}, t_{\text{peak}})$.

Next let us mention the dependence of the CFPE on the model parameters. Figure 3 shows the cocoon emission from the $z75BSG$ progenitor with different parameter sets of $(\eta_j, \theta_j)$ fixing $\alpha = 1$ (see also Table 1). The solid line corresponds to our fiducial case, and the cases in which $\eta_j$ is 10 times larger (thick dotted line) or smaller (thin dotted line), and $\theta_j$ is two times larger (thick dot-dashed line) or smaller (thin dot-dashed line) are shown. One can see that, by increasing $\eta_j$, the peak luminosities increase and the durations become shorter, and by increasing $\theta_j$, the durations become longer, but the peak luminosities are almost the same. Using this information, we can probe $(\eta_j, \theta_j)$, i.e., the efficiency and the half-opening angle of the jet inside the progenitor, from the observation of the cocoon emission once the progenitor is fixed.

Now we investigate the spectral evolution of CFPEs in order to discuss the detectability using current and future facilities. The observed fluxes in each frequency band can be described as

$$F_{\lambda_{\text{obs}}} (t_{\text{obs}}) d\lambda_{\text{obs}} \approx B_{\lambda} (T_{c}(t)) d\lambda \times \frac{R(t) \Delta \rho c}{\tau(t) D_L(z)^2}, \quad (20)$$

where $t_{\text{obs}} = t(1+z)$, $\lambda_{\text{obs}} = \lambda(1+z)$, and $D_L(z)$ is the luminosity distance of the source. We simply assume that the spectra are blackbody spectra, $B_{\lambda}(T) = (2hc^2/\lambda^5)(\exp(hc/\lambda k_b T) - 1)^{-1}$ for $R_s < R < R_{\phi}$ with $h$ being Planck's constant. For a given wavelength, the flux at wavelength $\lambda$ takes its maximum at $hc/\lambda \approx 2.89k_B T_c(z) t_{\text{peak}}(1+z)$ as long as it occurs before $t = t_{\text{peak}}$. This means that the observed flux takes its maximum at

$$t_{\text{obs,peak}}(\lambda_{\text{obs}}) \approx \min \left[ t_{\text{peak}}(1+z), \left( \frac{1.74 t_{\text{sat}}}{1+z} \right)^{1/2} \left( \frac{h \lambda_{\text{obs}}}{k_B T_{c,\text{bo}}} \right)^{-3/2} \right], \quad (21)$$

where $t_{\text{sat}} = R_{\text{sat}}/v_{\text{sat}}$. 

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**Figure 2.** Bolometric luminosities of CFPE from the progenitors in Table 1. We fix $\alpha = 1$, $\eta = 6.2 \times 10^{-4}$, and $\theta_j = 0.1$, and assume an exponential cutoff at $t = t_{\text{peak}}$.

(A color version of this figure is available in the online journal.)

**Figure 3.** Bolometric luminosities of CFPE from the $z75BSG$ progenitor with different parameter sets of $(\eta_j, \theta_j)$ shown in Table 1. We fix $\alpha = 1$, and assume an exponential cutoff at $t = t_{\text{peak}}$.

(A color version of this figure is available in the online journal.)
Figures 4, 5, and 6 show the expected AB magnitudes of CFPE from Pop III stars in each band of the optical to infrared. We show the cases at $z = 6$ and 15 including the effect of Ly$\alpha$ absorption. Photons with observed wavelengths $\lambda_{\text{obs}} \lesssim 0.85 \mu m$ and $\lesssim 1.9 \mu m$ are almost completely absorbed at $z = 6$ and 15, respectively, due to the un-ionized interstellar medium. We neglect extinction due to intergalactic dust (Weinmann & Lilly 2005). The horizontal line shows the expected 10$\sigma$ detection limit using JWST with an exposure time of 100 hr. The effect of the Ly$\alpha$ absorption is included. (A color version of this figure is available in the online journal.)

Figures 4, 5, and 6 show the expected AB magnitudes of CFPE from Pop III GRBs with $M_{\text{ZAMS}} = 915 M_\odot$ at $z = 6$ (left) and $z = 15$ (right). We fix $\alpha = 1$, $\eta_j = 6.2 \times 10^{-4}$, and $\theta_j = 0.1$. The horizontal line shows the anticipated 10$\sigma$ detection limit using JWST with an exposure time of 100 hr. The effect of the Ly$\alpha$ absorption is included. (A color version of this figure is available in the online journal.)

5. SUMMARY AND DISCUSSION

We have investigated the possibility that hot plasma cocoons associated with successful GRB jets produce detectable signals. By using a simple model, we have calculated the formation and the evolution of cocoons before and after jet breakouts, and the photospheric emissions from the cocoon for Pop III stars in each band of the optical to infrared. We show the cases at $z = 6$ and 15 including the effect of Ly$\alpha$ absorption. Photons with observed wavelengths $\lambda_{\text{obs}} \lesssim 0.85 \mu m$ and $\lesssim 1.9 \mu m$ are almost completely absorbed at $z = 6$ and 15, respectively, due to the un-ionized interstellar medium. We neglect extinction due to intergalactic dust (Weinmann & Lilly 2005). The horizontal line shows the expected 10$\sigma$ detection limit using JWST with an exposure time of 100 hr. The effect of the Ly$\alpha$ absorption is included. (A color version of this figure is available in the online journal.)

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Figures 4, 5, and 6 show the expected AB magnitudes of CFPE from Pop III GRBs with $M_{\text{ZAMS}} = 70 M_\odot$. (A color version of this figure is available in the online journal.)
III or metal-poor BSG and WR progenitors. We have found that the brightness can be highly progenitor-dependent, i.e., the bolometric luminosity of the Pop III or BSG progenitors can be \( \gtrsim 100 \) times larger than that of the WR progenitor. Thus, CFPE can be a diagnostic indicator of Pop III or BSG GRBs. We have shown that CFPE from Pop III GRBs even at \( z \sim 15 \) can be detectable in infrared bands as transients of years using JWST. We have also considered the possibility that GRBs from metal-poor BSGs occur at relatively lower redshift, \( z \lesssim 1.12 \). In these cases, our model predicts rebrightenings in optical/infrared bands from months to a year after the GRB. Based on these results, we have proposed that the observed ultra-long GRB111209A has been potentially followed by CFPE recently up to an AB magnitude of \( \lesssim 26 \), which could be detectable.

The local event rate of an ultra-long GRB is estimated as \( \sim 9 \times 10^{-3} \) Gpc\(^{-3}\) yr\(^{-1} \) (Gendre et al. 2013) without taking into account the beaming effect. Since CFPE can be seen from the off-axis direction of the jet, the all-sky rate of the events can be as high as \( \sim 2(\theta_j / 0.1)^{-2} \) Gpc\(^{-3}\) yr\(^{-1} \), which is still much lower than an SN Ibc rate of \( \sim 2 \times 10^4 \) Gpc\(^{-3}\) yr\(^{-1} \) (Madau et al. 1998). Nevertheless, they might have been already observed as a peculiar-type SNe given that the duration is long (\( \lesssim 100 \) days) and the total radiation energy is large (\( \gtrsim 10^{50} \) erg). Particularly in cases with a relatively energetic jet where \( \eta_j \) is 10 times larger than our fiducial value, total radiation energy becomes as large as \( \lesssim 10^{51} \) erg (see Table 1), which can be comparable to that of the observed superluminous supernovae (SLSNe). The energy source of SLSNe is still highly controversial (Gal-Yam 2012 and references therein). Given the local SLSN rate of \( \sim 10 \) Gpc\(^{-3}\) yr\(^{-1} \), some of them might originate from cocoon fireballs associated with metal-poor BSG GRBs.

In Figure 8, we compare the light curve of cocoon emission with that of various types of SNe. We plot the bolometric magnitude of the cocoon emission: the \( \eta_{75} \) model with \( \eta_j \) 10 times larger than our fiducial value (thick solid line) and the \( s40WR \) model (thin solid line). For the SNe, we plot the absolute magnitude in the observed \( R \) band. We show a class I SLSN (PTF09cnd; thick dotted line; Quimby et al. 2011), a class II SLSN (SN2006gy; thin dotted line; Smith et al. 2007), Type Ic SNe associated with a GRB or hypernova (SN1998bw; thick dot-dashed line; Galama et al. 1998), and an average of the observed Type Ibc SNe (thin dot-dashed line; Drout et al. 2011).

From Figure 8, one can see that the CFPE from metal-poor BSG GRBs can be similar to SLSNe at least in terms

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12 Actually, Tornatore et al. (2007) showed that Pop III star formation could last up to \( z \sim 2 \).
of the energetics and the timescale. In order to distinguish between, or identify, cocoon emission and such a class of SNe, more detailed radiation transfer calculations of the cocoon emission are required, which is beyond the scope of this paper. Figure 8 also shows explicitly that cocoon emission from the WR progenitor is much dimmer than the observed GRB SNe, or typical Type Ibc SNe. We can expect that cocoon emission associated with WR GRBs are hard to detect since they would be hidden by possibly associated SNe or the host galaxy.

Cocoon emission is observationally characterized by three parameters \( \xi, \eta, \theta_j \). For a fixed parameter set of \( \alpha, \eta_j, \theta_j \), the observed characteristics highly depend on the progenitor mass as shown in Figure 2. This means that one could constrain the mass of the Pop III or BSG progenitor by detecting the CFPE. On the other hand, if the progenitor mass is fixed, one can constrain \( \eta_j, \theta_j \) from the observed light curve (see Figure 3). This means that one can potentially probe, e.g., the accretion disk formation and the jet production and propagation before the jet breakout, which otherwise cannot be seen using only electromagnetic signals of the prompt emission. The observation of prompt gamma-ray and afterglow emission from the relativistic jet could provide a stronger constraint on \( \eta_j, \theta_j \) and also \( \alpha \) combined with the detection (or even non-detection) of cocoon emission.

Although our calculations are based on several simplified assumptions, we can expect that the results are qualitatively correct. Our model parameters \( \alpha, \eta_j, \theta_j \), which are generally progenitor- and time-dependent, could be refined by numerical studies on the accretion-disk formation and the jet propagation in the collapsing stars.

In this paper, we assume that the inner and outer parts of a cocoon, i.e., shocked stellar matter and shocked jet matter, are fully mixed (Equation (8)). This estimate gives the maximum baryon loading on the cocoons. Let us consider the cases where the mixing of the cocoon is suppressed by a factor \( \xi < 1 \), i.e., \( M_{\text{c,bo}} \rightarrow \xi M_{\text{c,bo}} \). The baryon loading and the optical depth of the cocoon at the jet breakout scale as \( n_c \propto \xi^{-1} \) and \( \xi_{\text{c,bo}} \propto \xi \), respectively. Then, from Equations (17)–(19), the CFPE becomes brighter with a higher peak energy and a shorter duration as \( t_{\text{peak}} \sim \xi^{3/4} \), \( L_{\text{peak}} \sim \xi^{-11/2} \), and \( \xi_{\text{peak}} \sim \xi^{-1/6} \). For example, in the case of the s40WR progenitor with \( \xi = 0.01 \), the CFPE is characterized by \( t_{\text{peak}} \sim 7.9 \times 10^4 \text{s} \), \( L_{\text{peak}} \sim 4.6 \times 10^{52} \text{erg s}^{-1} \), and \( \xi_{\text{peak}} \sim 48 \text{eV} \). Such emission from a mildly relativistic cocoon fireball is discussed in, e.g., Pe’er et al. (2006).

The dynamics of cocoons just after jet breakout, i.e., \( R_s \leq R \leq R_{\text{sat}} \), would be more complex than our model and can also be refined with the aid of numerical simulations. As for the coating phase of the cocoon fireball, i.e., \( R_s \leq R \leq R_{\text{ph}} \), more detailed radiation transfer calculations are needed to distinguish cocoon emission from other competing sources, e.g., various types of SNe and galaxies.

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Note added. After the submission of this paper, Levan et al. (2013) reported that GRB111209A was followed by a bright optical/JR emission with an AB magnitude of \( \lesssim 24 \) from 10 to 100 days after the prompt emission. Although the observed spectrum is softer than the prediction of our model here, the luminosity and the duration are roughly consistent with CFPE from a metal-poor BSG progenitor with a relatively energetic jet (\( \eta_j \times 10 \)).

REFERENCES

Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Bromberg, O., Nakar, E., Piran, T., & Sari, R. 2011, ApJ, 740, 100
Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJL, 527, L5
Chen, W.-X., & Beloborodov, A. M. 2007, ApJ, 657, 383
Clark, P. C., Glover, S. C. O., Klessen, R. S., & Bromm, V. 2011, ApJ, 727, 110
de Souza, R. S., Yoshida, N., & Ioka, K. 2011, A&A, 533, A32
Drout, M. R., Soderberg, A. M., Gal-Yam, A., et al. 2011, ApJ, 741, 97
Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372
Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. 1998, Natur, 395, 670
Gal-Yam, A. 2012, Sci, 337, 927
Gendre, B., Stratta, G., Atteia, J. L., et al. 2013, ApJ, 766, 30
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Heger, A., & Woosley, S. E. 2010, ApJ, 724, 341
Hosokawa, T., Omukai, K., Yoshida, N., & Yorke, H. W. 2011, Sci, 334, 1250
Inoue, S., Omukai, K., & Ciardi, B. 2007, MNRAS, 380, 1715
Ioka, K., & Mészáros, P. 2005, ApJ, 619, 684
Kawanaana, N., Piran, T., & Krolik, J. H. 2013, ApJ, 766, 31
Komissarov, S. S., & Barkov, M. V. 2010, MNRAS, 402, L25
Kawanaka, N., Piran, T., & Krolik, J. H. 2013, ApJ, 766, 31
Kawanaka, N., Piran, T., & Krolik, J. H. 2013, ApJ, 766, 31
Komissarov, S. S., & Barkov, M. V. 2010, MNRAS, 402, L25
Kumar, P., Narayan, R., & Johnson, J. L. 2008, MNRAS, 388, 1729
Lazzati, D., & Begelman, M. C. 2005, ApJ, 629, 903
Levan, A. J., Tanvir, N. R., Smart, R. L., et al. 2013, ApJ, submitted (arXiv:1302.2352)
Mackayen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Madau, P., & Panagia, N. 1998, MNRAS, 297, L17
Matzner, C. D. 2003, MNRAS, 345, 575
McKee, C. F., & Tan, J. C. 2008, ApJ, 681, 771
McKinney, J. C., & Gammie, C. F. 2004, ApJ, 611, 977
Mészáros, P. 2013, APh, 43, 134
Mészáros, P., & Rees, M. J. 2001, ApJL, 556, L37

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