Nearby SN-associated GRB 190829A: Environment, Jet Structure, and VHE Gamma-Ray Afterglows

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Received 2021 February 18; revised 2021 May 1; accepted 2021 June 16; published 2021 August 24

Abstract

We present a self-consistent paradigm to interpret the striking features of nearby low-luminosity GRB 190829A. Its prompt gamma-ray lightcurve has two separated pulses. We propose that the interaction of the hard prompt gamma-ray photons \(E_p = 624^{+2432}_{-303}\) keV of its initial pulse with the dusty medium \(A_V \sim 2.33\) not only results in the second soft gamma-ray pulse \(E_p \sim 12\) keV but also makes a pre-accelerated \(e^\pm\)-rich medium shell via the \(\gamma\gamma\) annihilation. In this paradigm, we show that the observed radio, optical, and X-ray afterglow lightcurves are well-fitted with the forward shock model. Its jet is almost isotropic \((\theta_j > 1.0\) rad\) with a Lorentz factor of \(\sim 35\), and the electron density of the \(e^\pm\)-rich medium shell is \(\sim 15\) cm\(^{-3}\), which is about seven times higher than the electron density of its normal surrounding medium. The GRB ejecta catches up with and propagates into the \(e^\pm\)-rich medium shell at a region of \(R = (4.07-6.46) \times 10^{19}\) cm. This results in a bright afterglow bump at \(\sim 10^3\) seconds after the GRB trigger. The predicted very high energy (VHE) gamma-ray emission from the synchrotron self-Compton process agrees with the H.E.S.S. observation. The derived broadband spectral energy distribution shows that GRB 190829A like nearby GRBs would be promising targets of the VHE gamma-ray telescopes, such as H.E.S.S., MAGIC, and CTA (Cerenkov Telescope Arrays).

Unified Astronomy Thesaurus concepts: Gamma-ray bursts (629)

1. Introduction

As the most intense burst phenomena in the universe, gamma-ray bursts (GRBs) and their afterglows are theoretically predicted as sources of very high energy (VHE) gamma-rays and cosmic rays (Waxman 1995; Milgrom & Usov 1995; Vietri 1995; Abdalla et al. 2019; Samuelsson et al. 2020). They are listed as the target sources of current and future telescopes in the GeV–TeV gamma-ray bands. Sub-TeV gamma-ray emission was first convincingly detected in the early afterglows of GRB 190114C with the Major Atmospheric Gamma Imaging Cerenkov Telescopes (MAGIC; MAGIC Collaboration et al. 2019a). Its broadband spectral energy distribution (SED) in the optical, X-ray, and gamma-ray bands can be well-explained with the models of synchrotron radiation and synchrotron self-Compton (SSC) process of the electrons accelerated in the jet (MAGIC Collaboration et al. 2019b; Derishev & Piran 2019; Wang et al. 2019). The SSC component is also marginally detected in GRB 130427A (Liu et al. 2013; Ackermann et al. 2014; Joshi & Razzaque 2019; Huang et al. 2020) and GRB 180720B (Duan & Wang 2019; Fraija et al. 2019; Wang et al. 2019). The window in the VHE gamma-ray band is opened for the GRB study. This is not only beneficial to reveal the radiation physics but is also critical for exploring the burst environment (e.g., Huang et al. 2021).

Typical GRBs happen in the high-redshift universe (Salvaterra 2015). VHE photons in the TeV-band suffer sharply because they are absorbed by the extragalactic background light (EBL) via the electron pair production (e.g., Stanee & Franceschini 1998; Dwek et al. 2005; Dwek & Kronrinh 2005; Aharonian et al. 2006; Mazin & Raue 2007; Franceschini et al. 2008; Meyer et al. 2012; Fermi-LAT Collaboration et al. 2018). This is a great obstacle for the detection of VHE gamma-rays from typical GRBs. The detection of the VHE gamma-ray afterglow of GRB 190114C is lucky because it is among the most energetic bursts to have happened at a relatively low redshift (\(z = 0.4245 \pm 0.0005\); Castro-Tirado et al. 2019). Note that nearby low-luminosity GRBs (LL-GRBs) seem to be a unique GRB population that is characterized by a high local event rate and large jet opening angle (e.g., Liang et al. 2007). It has been proposed that they are considerable sources of VHE photons and cosmic rays (Murase 2019).

Interestingly, GRB 190829A is a LL-GRB that is associated with a broad-line type Ic supernova, SN 2019yow (de Ugarte Postigo et al. 2019; Hu et al. 2021). It is among the nearest GRBs with a redshift of \(z = 0.0785 \pm 0.0005\) (Valeev et al. 2019). Its prompt gamma-rays have two distinct pulses: a hard-weak pulse followed by a soft-bright pulse with a separation of about 50 s (Chand et al. 2020). However, the two pulses do not share the same \(L_{iso} - E_p\) relation that is usually seen in long GRBs (Lu et al. 2012). Its high energy afterglow was detected by H.E.S.S. at 4.3 hr after the GRB trigger (de Naurois & H.E.S.S. Collaboration 2019). Zhang et al. (2020) suggested that the VHE gamma-ray afterglow is produced in the external inverse-Compton scenario for seed photons supplied by the second emission episode of the prompt gamma-rays, but the bump has a long delay to the prompt gamma-rays. The optical and X-ray light curves of GRB 190829A afterglow have an achromatic bump with a rapid increase at around 700 s after the GRB trigger and the X-ray afterglow faded as a single power-law up to more than 110 days without a detection of the jet break. The origin of the bump is uncertain. It has been proposed that the bump may be due to the activity of the GRB central engine (Chand et al. 2020) or the dipole radiation of its remnant magnetar plus the forward shock emission.

\(3\) The H.E.S.S. observational data was published (H.E.S.S. Collaboration et al. 2021) right after our manuscript was accepted, and we added the H.E.S.S. observational data in Figure 3 during the proof’s reading phase without changing any for our model parameters.
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454 spectrum of
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527 Prompt gamma-ray light curve of GRB 190829A observed with
571 The Astrophysical Journal,
631 spectrum as observed with Fermi
421 the interpretation of the radio afterglow is also debated.
410 The X-ray afterglow and lasted longer
388 15.5 GHz and 1.3 GHz comes from the reverse and forward
322 presents a self-consistent interpretation of its features. We
355 radio emissions are from the wide jet component.
311 that the radio, optical, X-ray afterglow data are well-
278 afterglow results from the SSC process of the electrons in the
282 axis observation of a two-component jet and late X-ray and
251 field, as proposed
224 makes alignment of their beginning times.
190 Data Analysis
119 and the peak photon energy of the \( \nu f_\nu \)
108 \( E_p = 11.8 \pm 1.1 \) keV in the burst rest frame, \( \alpha = -0.92 \pm 0.62 \),
102 one can observe that the X-ray and optical light curves show the same
97 we collect the afterglow data from the literature and GCN reports,
96 and their light curves are shown in the left-hand panel of Figure 2.
90 that the optical light curve is shown with the
87 with exponential-cutoff model, yielding a photon index of
80 \( \nu 2432 \) keV in the burst rest frame
75 GRB 190829A was detected at an even later epoch than the X-ray afterglow and lasted longer (Rhodes et al. 2020).
68 that the radio afterglow in
62 proposed that the bump is a signature of medium density jump. The radio
56 in some GRBs, such as GRB 970508 (Castro-Tirado & Gorosabel 1999), Dai & Lu (2002) proposed
44 that the radio afterglow data are well-fitted with
32 for the optical and X-ray light curves show the same
23 the X-ray and optical data has been corrected by extinctions from our Galaxy
17 3. A Self-consistent Paradigm and Multiwavelength Afterglow Modeling
10 Basing on this data analysis, we propose a paradigm to explain both the prompt and afterglow emission of GRB 190829A. We outline the paradigm as follows. First, the ejecta powered by the central engine of GRB 190829A is quasi-isotropic because no jet break is detected later than 110 days past the GRB trigger. Second, the initial hard gamma-ray pulse is produced by internal shocks of the ejecta. Third, the hard gamma-ray photons \( (E_\gamma = 624^{+2425}_{-303}) \) keV in the burst rest frame) are scattered by the density medium \( (\Delta V = 2.33) \), resulting the second soft gamma-ray pulse \( (E_\gamma = 11.8 \pm 1.1 \) keV in the burst rest frame\), similar to that proposed by Shao & Dai (2007). Fourth, the interaction of the gamma-ray photons with the dust leads to an \( e^+ \)-rich medium shell via the \( \gamma\gamma \) annihilation, and the \( e^\pm \)-rich medium shell is also
6 Collected from https://www.swift.ac.uk/xrt_spectra/.
The observed parameters of the jet and their 1σ confidence levels are shown as follows: the isotropic kinetic energy \( E_{\gamma,\text{iso}} \) is \( 51.01^{+0.43}_{-0.33} \) of GRB 190829A, the initial bulk Lorentz factor \( \gamma_0 = 1.55^{+0.17}_{-0.33} \), the circumburst medium number density \( n_0 = 0.34^{+0.56}_{-0.70} \), the electron energy fraction \( \epsilon_e = -0.49^{+0.46}_{-0.22} \), the magnetic field energy fraction \( \epsilon_B = -3.22^{+0.21}_{-0.80} \), and the spectrum index of electrons \( p = 2.12^{+0.08}_{-0.17} \). The parameters of the \( e^\pm \)-rich shell are \( R_{\text{obs}}(\text{cm}) = 16.61^{+0.30}_{-0.14} \) and \( R_{\text{iso}}(\text{cm}) = 16.81^{+0.38}_{-0.15} \), and \( k = 6.87^{+3.64}_{-2.55} \).

In contrast to typical GRBs, the jet of GRB 190829A is middle relativistic, with \( \Gamma_0 \approx 35 \). No jet break is observed until \( t > 5.5 \times 10^8 \) s, when the afterglow is dimmer than the host galaxy. Taking the jet break time \( t_j > 5.5 \times 10^8 \) s, we calculate the jet half-opening angle with (Fraioli et al. 2001)

\[
\theta_j = 0.057 \left( \frac{t_j}{1 \text{ day}} \right)^{3/8} \left( \frac{1 + z}{2} \right)^{-3/8} \left( \frac{E_{\gamma,\text{iso}}}{10^{53} \text{ ergs}} \right)^{-1/8} \left( \frac{\eta_j}{0.2} \right)^{1/8} \left( \frac{n}{0.1 \text{ cm}^{-3}} \right)^{1/8},
\]

where \( E_{\gamma,\text{iso}} \) and \( \eta_j \) are the isotropic gamma-ray energy and radiative efficiency, respectively. The circumburst medium density is taken as \( n_0 \). The GRB efficiency is calculated as \( \eta_j = E_{\gamma,\text{iso}}/(E_{\gamma,\text{iso}} + E_{\text{iso}}) = 17\% \) with \( E_{\text{iso}} = 2 \times 10^{50} \) erg (Tsvetkova et al. 2019). We obtain \( \theta_j > 1.0 \) rad, which indicates that the ejecta are almost isotropic.

### 4. VHE Gamma-Ray Afterglows

H.E.S.S. detected the VHE gamma-rays of the GRB 190829A afterglow with a confidence level of 5σ in the time interval from \( t = T_0 + 4 \text{h}20 \text{m} \) to \( t = T_0 + 7 \text{h}54 \text{m} \), but the observed flux is not released (de Naurois & H.E.S.S. Collaboration 2019), where \( T_0 \) is the trigger time. Therefore, our earlier afterglow modeling does not take the VHE gamma-ray afterglow into account. We examine whether our model calculation satisfies the observation with H.E.S.S. We also

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**Figure 2.** Left-hand panel: Multiwavelength afterglow lightcurves (dots) of GRB 190829A along with our fits with the forward shock model (lines). The shaded region marks the afterglows are dimmer than the emission of the host galaxy. Right-hand panel: Joint optical-X-ray afterglow spectrum (dots) observed in the time interval of \([3,4] \times 10^8\) s of GRB 190829A along with our fit with a single power-law function (dashed lines). The optical data are extinction-corrected for our Galaxy only. Extinction and HI absorption of both our Galaxy and the GRB host galaxy are considered in our spectral fit.
curves are adopted from Bai et al. (2021) and Collaboration et al. 2021. The High Altitude Shower Observatory (H.A.S.O.) and Telescope Arrays (detectable with H.E.S.S., MAGIC and CTA) afterglow at this time epoch is convincingly EBL absorption effects into account. The ejecta is considerable, especially in the early epoch. Taking the €-rich medium shell is present a further discussion of whether or not it can be detected with the current and near-future telescopes.

Figure 3 shows the 0.5 TeV and 0.2–4 TeV (H.E.S.S. energy band; H.E.S.S. Collaboration et al. 2021) lightcurves and the SEDs at 1200 seconds (the peak time of the light curve) and 2 × 104 seconds (in the time interval of H.E.S.S. observation for GRB 190829A). The light curve is corrected for the EBL absorption (Domínguez et al. 2011). One can find that VHE afterglow is very bright while the ejecta propagates in the €-rich shell. The afterglow light curve of GRB 190114C in the 0.5 TeV band is also shown in Figure 3 for comparison. One can find that flux of the VHE gamma-ray afterglow of GRB 190829A is comparable to GRB 190114C at the epoch from [2 × 105, 1 × 107] s.

The SEDs illustrate that the γγ annihilation effect in the ejecta is considerable, especially in the early epoch. Taking the EBL absorption effects into account (Domínguez et al. 2011), the VHE afterglow at this time epoch is convincingly detectable with H.E.S.S., MAGIC and CTA (Cerenkov Telescope Arrays), but is not detectable with LHAASO (Large High Altitude Shower Observatory). The SED at t = T0 + 2 × 104 s shows that the VHE emission can be detected with H.E.S.S., which is consistent with the observations (de Naurois & H.E.S.S. Collaboration 2019). It is also marginally detectable with MAGIC and convincingly detectable with CTA.

5. Conclusions and Discussion

We have revisited the multiwavelength data of nearby LL-GRB 190829A and presented a self-consistent paradigm to interpret its features by assuming that an €-rich medium shell resulted from the interaction between the hard gamma-ray photons and dense medium pre-accelerated by the prompt gamma-rays. We show that the observed radio, optical, X-ray and VHE gamma-ray afterglows can be attributed to the emission from the synchrotron radiation and the SSC process of the electron accelerated in the forward shocks. The results of our fit to the multiwavelength afterglow light curves show that the ejecta of GRB 190829A is almost isotropic (θ > 1.0 rad) and middle relativistic (Γ0 ≈ 35). The electron density of the €-rich medium shell is ~15 cm−3, which is about seven times higher than the electron density of its normal surrounding medium. Based on the model parameters derived in our analysis, we calculate the VHE gamma-ray light curve and the SED at the peak time of the light curve. We have found that its VHE gamma-ray emission is convincingly detectable with H.E.S.S., MAGIC, and CTA at its peak time.

The dusty medium should be essential to interpret the data of GRB 190829A. The detection of associated SN 2019oyw with GRB 190829A confirms its progenitor as a massive star. Liang et al. (2007) proposed that local LL-GRBs would be a unique GRB population with low luminosity, small beaming factor, and large local event rate. The ejecta of GRB 190829A is middle relativistic and quasi-isotropic, which is consistent with the features of the local LL-GRBs. Our joint optical-X-ray spectral analysis reveals that the ambient medium of the GRB is extremely dusty. By correcting the i band SN data with a host galaxy extinction of Ei,B−V = 0.757, and by assuming a Milky Way (MW) extinction law,5 we find that the peak absolute magnitude of SN 2019oyw at i band is MI = −18.3 ± 0.01 mag, which is comparable to SN 2006aj (MI = −18.36 ± 0.13 mag) and SN 2010bh (MI = −18.58 ± 0.08 mag) (Hu et al. 2021).

We collect the AV and NH values of the GRBs associated with SN from literature, as reported in Table 1. Figure 4 shows NH as a function of AV. A sample of typical long GRBs taken from literature, together with the typical dust-to-gas ratio for the Local Group (LG) environment NH/AV = 1.6 × 1022 cm−2 mag−1 (Covino et al. 2013), is also shown in Figure 4. One can observe that the AV value of GRB 190829A is the largest among the SN-associated GRB sample, although it is still not significantly distinct from the typical GRBs. It closes to the dust-to-gas ratio for the LG environment but is above the ratio, as are most long GRBs.

It was proposed that the interaction between the prompt gamma-ray pulse and the medium can not only pre-accelerate the ambient medium to a high Lorentz factor but is also accompanied by €- loading via the pair production process (e.g., Madau & Thompson 2000; Thompson & Madau 2000; Mészáros et al. 2001). This may affect the GRB afterglow behaviors (e.g., Beloborodov 2002). We suspect that the €-rich medium shell results from the interaction of the initial extremely hard gamma-ray photons of GRB 190829A with the dust.

5 The Ei,B−V value reported in Chand et al. (2020) is 1.04, which is found by adopting a the Small Magellanic Cloud (SMC) extinction law. Note that the difference in time interval selection for joint spectral fit may lead us to derive a different extinction value.
Table 1
Properties of the GRB-SN Samples with Multicolor Light Curves

| GRB/SN     | Redshift* | AV_{SD}(mag)* | N_{H}(10^{21} \text{cm}^{-2}) | T(s)$^\text{b}$ |
|-----------|-----------|----------------|-------------------------------|--------------|
| 980425/1998bw | 0.0085 | 0.17 ± 0.02 | ... | ... |
| 030329/2003dh | 0.1686 | 0.39 ± 0.15 | ... | ... |
| 050525A/2005nc | 0.606 | 0.36 ± 0.05 | 5.9 ± 1.6 | T_{0} + 151542 |
| 060218/2006aj | 0.0334 | 0.13 ± 0.01 | 3.1 ± 0.6 | T_{0} + 7028 |
| 081007/2008bw | 0.5295 | 0.31 ± 0.25 | 7.7 ± 1.5 | T_{0} + 8027 |
| 091127/2009nz | 0.4904 | 0.17 ± 0.15 | 1.1 ± 0.6 | T_{0} + 13229 |
| 100316D/2010bh | 0.0592 | 0.43 ± 0.03 | 20 ± 8 | T_{0} + 13397 |
| 101219B/2010ma | 0.5518 | <0.1 | 0.7 ± 0.5 | T_{0} + 362754 |
| 111209A/2011kl | 0.677 | 0.121 ± 0.036 | 2.7 ± 0.8 | T_{0} + 267284 |
| 130427A/2013c | 0.3399 | 0.13 ± 0.06 | 1.22 ± 0.18 | T_{0} + 712132 |
| 130702A/2013dx | 0.677 | 0.3 ± 0.07 | 1.4 ± 0.3 | T_{0} + 1478125 |
| 130831A/2013fu | 0.4791 | 0.06 ± 0.04 | 0.2 ± 0.2 | T_{0} + 251766 |
| 140606B/iPTF14bufu | 0.384 | 0.47 ± 0.41 | 6 ± 5 | T_{0} + 187980 |
| 171205A/2017iuk | 0.0368 | 0.155$^c$ | 1.2 ± 0.6 | T_{0} + 749534 |
| 190829A/2019oyw | 0.0785 | 2.33 | 5.79 ± 0.53 | T_{0} + (3 – 4) × 10^{7} |

Notes.

* The values of AV, redshift z are taken from Li et al. (2018), except for 111209A from Kann et al. (2018), 140606B/iPTF14bufu from Cano et al. (2015), and 171205A/2017iuk from Suzuki et al. (2019).

$^b$ NH values are taken from the XRT Catalogue entry of the Swift website and T is the corresponding time for extracting the XRT spectrum.

is ~10^{3} s. Our fit indicates that the e$^\pm$ -rich medium shell is at a region of R = (4.07–6.46) × 10^{16} cm. This is generally consistent with the forward shock region for the GRB afterglows (Mu et al. 2016). The time delay for the ejecta catching up with the e$^\pm$ -rich medium shell is estimated as $\Delta t = R/cT_{0}^{2} \approx 1.1 \times 10^{3}$ seconds, without considering the deceleration of the ejecta. $^6$ This is consistent with the observation.

We acknowledge the use of the public data from the Swift data archive and the UK Swift Science Data Center. This research has made use of the CTA instrument response functions provided by the CTA Consortium and Observatory, see http://www.cta-observatory.org/science/cta-performance/ (version prod3b-v2) for more details. This work is supported by the National Natural Science Foundation of China (grant No.12133003, 11851304, and U1731239) and the Guangxi Science Foundation (grant No. 2017AD22006).

Figure 4. N_{H} as a function of AV of GRBs associated with an associated SNe (green-diamond dots) in comparison with typical long GRBs (gray-dots and triangles) from Covino et al. (2013). The triangle represents the upper or lower limit. GRB 190829A-SN 2019oyw is marked as a red star. The red-dashed line shows typical dust-to-gas ratio for the Local Group (LG) environment (Covino et al. 2013).

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$^6$ The ejecta may move in a cavity because the medium is pre-accelerated by the prompt gamma-rays (Beloborodov 2002).
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