An Evolving GeV Spectrum from Prompt to Afterglow: The Case of GRB 160509A

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Abstract

We present the high-energy emission properties of GRB 160509A, from its prompt mission to late afterglow phase. GRB 160509A contains two emission episodes: 0–40 s and 280–420 s after the burst onset ($t_0$). The relatively high flux of GRB 160509A allows us to establish an evolving spectrum above 100 MeV. During the first emission episode, the >100 MeV spectrum is soft with $\Gamma \gtrsim 3.0$, which can be smoothly connected to keV energies with a Band function with or without a high-energy cutoff. The >100 MeV spectrum rapidly changes to a hard spectrum with $\Gamma \lesssim 1.5$ after $t_0 + 40$ s. The existence of very energetic photons, e.g., a 52 GeV that arrives at $t_0 + 77$ s and a 29 GeV that arrives at $t_0 + 70$ ks, is hard to reconcile by the synchrotron emission from forward-shock electrons, but is likely due to an inverse-Compton (IC) mechanism, e.g., synchrotron self-Compton emission. A soft spectrum ($\Gamma \sim 2$) between 300 and 1000 s after the burst onset is also found at a significance of about 2 standard deviations, which suggests a different emission mechanism at work for this short period of time. GRB 160509A represents the latest example where IC emission has to be taken into account in explaining the afterglow GeV emission, which had been suggested long before the launch of the Fermi Large Area Telescope.

Key words: gamma-ray burst: individual (GRB 160509A) – radiation mechanisms: non-thermal – methods: data analysis

1. Introduction

Since 2008, the Large Area Telescope (LAT) on board the Fermi satellite, working at >30 MeV energies, has detected over 100 gamma-ray bursts (GRBs) during the prompt keV–MeV emission phase and/or the afterglow phase. The main characteristics of the >100 MeV emission of GRBs before 2011 is described in Ackermann et al. (2013).

The afterglow >100 MeV emission is typically characterized by a power-law-like decay after a peak time (which sometimes coincides with the prompt emission), and a mean photon index of about 2 for several well-studied cases of bright LAT GRBs. The synchrotron radiation of shock-accelerated electrons is usually thought to be the dominant radiation mechanism of the late-time LAT emission up to ∼10 GeV (Kumar & Barniol Duran 2009; Zou et al. 2009). However, there is a maximum photon energy that synchrotron radiation can reach in the context of Fermi acceleration in the shocks, which in general cannot be much higher than a few GeV in the observer’s frame at the deceleration time $t_{\text{dec}}$ (Piran & Nakar 2010).

Emission above 10 GeV, well after the prompt emission, has been detected by the LAT, including GRB 940217 (Hurley et al. 1995), GRB 130427A (Fan et al. 2013), GRB 130907A (Tang et al. 2014), and GRB 131231A (Liu et al. 2014). For the very bright and very long >100 MeV afterglow of GRB 130427A, inverse-Compton (IC) radiation was argued to be responsible for the very energetic photons seen especially at late times (Liu et al. 2013; Tam et al. 2013; Ackermann et al. 2014), again mainly based on the above maximum synchrotron photon energy argument. The >100 MeV emission from GRB 131231A is also well described by a hard power law with the photon index ($\Gamma \approx 1.5$) in the first ∼1300 s after the trigger, and the most energetic photon has an energy of about 62 GeV, arriving at ∼520 s post-trigger (Liu et al. 2014).

The relatively small collection area of the LAT has limited the study of such energetic photons (e.g., > a few GeV) to the relatively bright GRBs. We note a recent work by Panaitescu (2017), who investigates the radiation mechanisms of the afterglow LAT emission using a large sample of GRBs. In this work, we focus on the very bright GRB 160509A, which, similar to GRB 130427A and GRB 131231A, emits several very energetic γ-rays.

2. Properties of GRB 160509A

GRB 160509A triggered several space instruments: Fermi’s LAT and GBM (Longo et al. 2016; Roberts et al. 2016), MAXI/GSC (Ono et al. 2016), Konus–Wind (Frederiks et al. 2016), CALET Gamma-Ray Burst Monitor (Yoshida et al. 2016), and INTEGRAL/SPI-ACS. In this work, we take the Konus–Wind trigger time as the reference time (i.e., $t_0 = 2016-05-09\,\text{UT}08:58:58.696$). The burst consists of a broad, multi-peaked pulse approximately from $t_0 - 10$ s to $t_0 + 30$ s, followed by several weaker emission episodes until around $t_0 + 380$ s (Frederiks et al. 2016). In particular, we identified a second emission episode around $t_0 + 280$ s to $t_0 + 420$ s (see Section 3.1). The Konus–Wind fluence in the 20 keV to 10 MeV energy band is $(2.90 \pm 0.35) \times 10^{-4}$ erg cm$^{-2}$. As seen by the Fermi GBM, the duration of the burst ($t_{\text{br}}$) is about 371 s (50–300 keV Roberts et al. 2016).

MAXI/GSC was triggered at UT 2016-05-09 09:04:16, i.e., $t_0 + 329.3$ s, and measured a photon spectral index of 1.26 ± 0.16, and the resultant 2–10 keV flux is $2.78 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. Based on the nondetection during the next transit at 10:37 UT on 2016 May 9 (around $t_0 + 5893$ s), the
MAXI/GSC team put an upper limit of 20 mCrab, i.e., about 4.8 × 10^{-10} erg cm^{-2} s^{-1}, on the X-ray flux at this time.

Swift’s X-ray Telescope (XRT) began data-taking of the burst at about t_0 + 7300 s. The XRT Light curve is obtained using the products extracted from the XRT repository\(^5\) (Evans et al. 2007, 2009) and is shown in Figure 1 as the data >7.2 ks after the burst, together with the energy flux reported for MAXI/GSC and derived from Fermi/GBM at early times.

We also extracted two 0.3–10 keV XRT spectra, corresponding to 7.2–7.6 ks and 14.2–76.9 ks after the burst roughly corresponded to the last two time bins of the LAT emission epoch. Both spectra are adequately described by single power laws, with photon index of Γ_X = 1.62^{+0.27}_{-0.25} and Γ_X = 1.99 ± 0.09, respectively. Thus, the X-ray spectrum does not evolve significantly, consistent with the analysis of Laskar et al. (2016).

The optical afterglow was first detected by Levan et al. (2016) at R.A. = 20:47:00.93, decl. = +76:06:29.2 (J2000). This position is used in the analyses presented in this Letter. It is confirmed to be fading by Cenko et al. (2016). The redshift of the burst was found to be z ≈ 1.17 with the Gemini North telescope (Tanvir et al. 2016). At this distance, its isotropic energy release in keV to MeV γ-rays, E_{γ,iso}, is about 1.06 × 10^{54} erg.

At radio wavelengths, VLA (Laskar et al. 2016) has observed GRB 160509A for weeks after the burst, and the authors claim evidence of reverse shock emission from these observations.

The HAWC detector observed the GRB over the prompt emission epoch and did not see any significant emission above ~300 GeV (Lennarz & Taboada 2016).

3. The Prompt Emission

3.1. The Two Main Emission Episodes

GRB 160509A is a bright GRB consisting of two emission episodes, 0–40 s and 280–420 s, separated by a long quiescent period. Figure 2 shows the light curves for each emission episode. For the first emission episode, we can see that LAT low energy (LLE) has two peaks, the first peak is around t_0 + 12 s and the second peak is around t_0 + 18 s, while in NaI’s n0 and BGO’s b0 detectors, the light curve has a rather broad maximum between 12 and 18 s. For the second emission episode (from 280 to 420 s), the emission was only detected up to around 500 MeV, and thus the BGO and LLE events do not show significant excess during this episode. Hence, the light curve obtained by the NaI’s n0 detector is shown.

3.2. Fermi GBM and LLE Spectral Analysis

During the main burst (or the first emission episode), all GBM detectors saw the emission from GRB 160509A. The GRB was also seen in the LLE (30 MeV–130 MeV) data from 7 to 28 s. To perform spectral fits, we made use of the GBM and LAT data available at the Fermi Science Support Center. For 0–40 s, we used time tagged event (TTE) data from the good-viewing detectors NaI n0, n3 and the BGO b0 detector, as well as the LLE data. For the second emission episode, we used TTE data from NaI n0 and BGO b0 detectors. The Band function is defined as (Band et al. 1993)

\[
f_{\text{Band}}(E) = A \begin{cases} \left( \frac{E}{E_{c \text{, LLE}}} \right)^\alpha \exp \left[ -\frac{(\alpha + 2)E}{E_p} \right] & : E < E_c, \\ \left( \frac{E}{E_{c \text{, LLE}}} \right)^\beta \exp \left( \frac{\beta - \alpha}{\alpha + 2} \right) & : E \geq E_c, \end{cases}
\]

where

\[
E_c = \frac{\alpha - \beta}{\alpha + 2} E_p,
\]

and the Band + High Cutoff model is defined as

\[
f_{\text{Band+Cut}}(E) = f_{\text{Band}}(E) \exp \left( -\frac{E}{E_{\text{cut}}} \right).
\]

In Equations (1), (3), and (2), A is the normalization factor at 100 keV in units of ph s^{-1} cm^{-2} keV^{-1}, α is the low-energy power-law photon index, β is the high-energy power-law photon index, E_p is the peak energy in the νφ_ν space in units of keV, E_c is the characteristic energy in units of keV, and E_{cut} is the high-energy cutoff in units of keV. Using RMFIT, we found that Band functions satisfactorily describe the first and second emission episodes including smaller time bins indicated in Table 1, suggesting a similar origin of the GBM and LAT emission for the first emission episode.

Motivated by the LAT analysis at >100 MeV during the 15–40 s that found a soft spectrum of Γ = −3.2 ± 0.2 (see Section 4), we further tested a Band+Cut function to fit the different time bins in the first emission episode defined in Table 1. We found that the Band+Cut function can significantly improve the fits for the time bins 0–40 s by Δχ^2-stat of 159.4, as well as for the time bins (b) 7–16 s and (c) 16–22 s. The best-fit model spectra for different time bins during the prompt emission are shown in Figure 3.

The high-energy cutoffs obtained in Table 1 are below 100 MeV, and such spectral cutoffs can be caused by γγ absorption. For such cutoffs <100 MeV, the target
can be estimated using this equation for the corresponding time bins, as shown in Table 1.

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| Model | $E_\gamma$ (keV) | $\alpha$ | $\beta$ | $\Delta\gamma$ | Photo Flux $^a$ | Energy Flux $^b$ | $E_{\text{cut}}$ (MeV) | $\Delta\sigma^{\text{stat}}$ | $\Gamma_b$ $^d$ |
|-------|-----------------|---------|--------|--------------|----------------|----------------|-----------------------|----------------|---------|
| 0–7   | Band            | 422.2 ± 70 | -1.14 ± 0.05 | -2.84 ± 0.27 | 414.9/369 | 4.23 ± 0.11 | 7.12 ± 0.34 | ... | ... |
| 7–16  | Band            | 461 ± 8.4  | -0.78 ± 0.01  | -2.38 ± 0.01 | 648.9±369 | 39.11 ± 0.17 | 93.1 ± 0.5 | ... | ... |
| ...   | Band+Cut        | 425.3 ± 2.1 | -0.75 ± 0.01 | -2.19 ± 0.01 | 562.1/368 | 38.94 ± 0.35 | 91.6 ± 0.9 | 56.2 ± 10.6 | 86.8 |
| 16–19 | Band+Cut        | 355.7 ± 8.9 | -0.60 ± 0.00 | -2.15 ± 0.01 | 572.3±369 | 45.11 ± 0.22 | 90.8 ± 0.5 | ... | ... |
| ...   | Band+Cut        | 326.0 ± 2.3 | -0.83 ± 0.01 | -2.01 ± 0.01 | 459.6/368 | 44.95 ± 0.58 | 90.5 ± 1.3 | 69.7 ± 12.2 | 112.7 |
| 22–40 | Band            | 218.8 ± 21 | -1.21 ± 0.03 | -2.22 ± 0.02 | 484.0±369 | 5.75 ± 0.07 | 7.35 ± 0.15 | ... | ... |
| 0–40  | Band            | 410.1 ± 7.0 | -0.89 ± 0.01 | -2.27 ± 0.01 | 768.5/369 | 18.79 ± 0.06 | 38.7 ± 0.2 | ... | ... |
| ...   | Band+Cut        | 384.5 ± 1.8 | -0.88 ± 0.01 | -2.12 ± 0.01 | 609.1/368 | 18.75 ± 0.14 | 38.5 ± 0.3 | 72.2 ± 10.6 | 159.4 |
| 280–358| Band            | 238.1 ± 55 | -0.93 ± 0.10 | -1.92 ± 0.11 | 461.4/233 | 1.49 ± 0.04 | 2.53 ± 0.09 | ... | ... |
| 358–420| Band            | 133.8 ± 22 | -1.23 ± 0.08 | -2.17 ± 0.13 | 501.8/233 | 2.92 ± 0.05 | 3.12 ± 0.11 | ... | ... |
| 280–420| Band            | 189.8 ± 30 | -1.15 ± 0.06 | -2.03 ± 0.09 | 661.6/233 | 2.13 ± 0.03 | 2.80 ± 0.07 | ... | ... |

Notes.

- $^a$ Time interval; in units of s.
- $^b$ 10–1000 keV; in units of photons (s cm$^{-2}$).
- $^c$ 10–1000 keV; in units of $\times10^{-7}$ erg (s cm$^{-2}$).
- $^d$ Bulk Lorentz factor calculated using Equation (4).

The redshift of GRB 160509A $z \approx 1.17$, so the bulk Lorentz factors $\Gamma_b$ can be calculated using this equation for the corresponding time bins, as shown in Table 1.

4. Fermi LAT Data Analysis and Results

The angle of the GRB position is about 32° from the LAT boresight when GBM was triggered and remains within the field of view until $\approx t_0 + 3000$ s. The GeV emission is first seen during the first emission episode and can be detected as late as about one day after the burst, although the GRB position had been occulted by the Earth several times over the course of a day.

We performed unbinned maximum-likelihood analyzes (gtlike) of a 15°-ROI centered at the GRB position to characterize the spectra of the >100 MeV $\gamma$-rays from the GRB onset to the afterglow phase.

The Fermi Science Tools v10r0p5 package was used to reduce and analyze the data using standard event selections. We selected photons of energies between 100 MeV and 300 GeV. Using the “P8R2_TRANSIENT020_V6” events increases the effective collection area, and thus the photon statistics, by $\sim$100% at 100 MeV, decreasing to $\sim$13% at...
1 GeV, compared to the event class “P8R2_SOURCE_V6.” So, we selected this event class for time bins lasting less than 300 s (i.e., all time bins between \(t_0\) and \(t_0 + 400\) s). For longer bins, the background becomes higher, and we selected the events classified as “P8R2_SOURCE_V6.” The instrument response functions for the corresponding event classes were used. To reduce the contamination from Earth albedo \(\gamma\)-rays, we excluded events with zenith angles greater than 100°.

The \(>100\) MeV photon spectrum from GRB 160509A is assumed to be a single power law, defined as

\[
dN/dE = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma}.
\]

The Galactic (gll_iem_v06.fits) and the isotropic (iso_P8R2_SOURCE_V6_v06.txt) components, as well as sources in the third Fermi catalog (Acero et al. 2015), were included in the background model for time bins after \(t_0 + 400\) s. The model includes 3FGL sources out to 15°, while the spectral parameters of sources with detection significance below 10, or variability index below 70, are fixed. Essentially, only the normalization factors of 3FGL J2005.2 +7752, 3FGL J2010.3+7228, and the two diffuse components are allowed to vary. For time bins before \(T_0 + 400\) s, the isotropic component suffices to describe the background photons, due to the dominance of the GRB emission over other sources in the ROI during these short-duration intervals. For the first three bins, the normalization factor of this isotropic component is fixed to unity. The photon index of the first data point \((0–7\) s) was fixed at 3.5 to derive the 90% confidence-level upper limit.

The derived light curve and the evolution of the photon index \((\Gamma)\) for the 0.1–100 GeV emission up to one day after GRB 160509A is shown in Figures 4(a) and (b).

We summarize the LAT emission properties at different times:

- **0–40 s:** the joint GBM/LLE analysis presented in Section 3.2 suggests a similar origin of the GBM and LAT emission. We note that the LAT photon index above 100 MeV is \(\Gamma = -3.2 \pm 0.2\) for the time bin 15–40 s, which is significantly softer than \(\beta\) of \(\approx 2.2\) obtained by the above joint GBM/LLE analysis for similar time bins. This is consistent with the better fit by a Band+Cut function (cf. Section 3.2). The cutoff during this first emission episode has been briefly mentioned by Kocevski & Longo (2016).
- **40–300 s:** after the first emission episode, the LAT emission quickly changes to a hard spectrum \((\Gamma = 1.42 \pm 0.12\) for the period 40–300 s). We note that the highest-energy photon (52 GeV) detected from GRB 160509A came during this period (77 s after burst onset).
- **300–1000 s:** there is a modified LAT emission between 300 and 1000 s (as compared to the hard spectrum seen before and after). This is identified via the soft spectrum \((\Gamma = 2.2 \pm 0.3)\) and the mini-bump in the LAT light curve (cf. Figure 4). To estimate the significance of the soft spectrum between 300 and 1000 s, as compared to the spectra seen before and after, we compare the index with the one obtained for the time 40–80,000 s, which is \((\Gamma = 1.5 \pm 0.2)\), and the difference is about 2 standard deviations.
- **After 1000 s:** the photon index for this epoch is \(\Gamma = 1.4 \pm 0.3\), which is again very hard. Noticeably, no emission below 1 GeV is seen (cf. Figure 4(c)).

Because of the spectral evolution, we also plot the light curves for two energy bands: 0.1–1 GeV and 1–100 GeV, as shown in Figures 4(c) and (d). It can be seen that during the 300–1000 s time bin, the emission is seen only below 1 GeV and not above 1 GeV. In contrast, the emission after 1000 s is dominated by \(>1\) GeV photons.

See, e.g., http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm.

\footnote{We also tested the robustness of the hard spectrum by also allowing the isotropic emission component to vary or keep it fixed and obtained \(\Gamma = 1.42 \pm 0.12_{\text{stat}} \pm 0.06_{\text{sys}}\).}
5. Discussion

GRB 160509A contains two emission episodes during the prompt phase, as well as a temporally extended GeV emission. The major finding of our current work is the changing spectrum of GRB 160509A above 100 MeV, from the prompt emission (i.e., within $t_{90}$) to the afterglow emission (i.e., up to a day after the burst; see Figure 4).

5.1. On the Origin of Hard GeV Afterglow

We established a hard spectrum ($\Gamma \leq 1.5$) that is seen during 40–300 s after the burst onset and after 1000 s. The hard spectrum, together with the 29 GeV photon arriving at 70 ks after burst, is difficult to reconcile by the synchrotron radiation of the forward-shock electrons, which is usually used to explain GeV emission with $\Gamma \geq 2$ (e.g., Kumar & Barniol Duran 2009; Zou et al. 2009). IC emission can play a significant role here (as suggested years ago by, e.g., Sari & Esin 2001; Zou et al. 2009).

The LAT emission in both epochs can be due to synchrotron self-Compton emission of forward-shock electrons, as is suggested to explain the $\Gamma \sim 1.5$ LAT spectrum for GRB 130427A and GRB 131231A (e.g., Liu et al. 2013, 2014). Panaitescu (2017) has presented light curves and spectra of 24 afterglows seen by the LAT and identified hard spectra above certain energies, i.e., 0.1–3 GeV for the GeV afterglow from a number of GRBs. For the observed hard spectrum $\Gamma \leq 1.5$ of GRB 160509A and assuming the electron spectral index, $p$, to be $\sim 2–3$, the electrons should be slow-cooling (i.e., $\nu_{\text{esc}} < \nu < \nu_{\text{esc}}$) and not fast-cooling (i.e., $\nu_{\text{esc}} < \nu < \nu_{\text{esc}}$), since fast-cooling electrons would produce a soft spectrum. For slow-cooling electrons, we have $F_{\nu} \propto \nu^{(11-9p)/8}$ in the ISM case and $F_{\nu} \propto \nu^{-p}$ in the wind case. Putting $p \sim 2.1$, the ISM model is in agreement with the power-law decay of the LAT flux $F_{\nu} \propto \nu^{-1.06}$ and the spectrum $\nu^{0.5}$ via $F_{\nu} \propto \nu^{-(p-1)/2}$.

5.2. On the Origin of the Possible Short-duration Soft GeV Emission

We also found evidence of a modified LAT emission between 300 and 1000 s (as compared to the hard spectrum identified above). This modified spectrum is mainly manifested via the soft spectrum ($\Gamma \sim 2$) and, to a lesser extent, by the mini-bump in the LAT light curve between 300 and 1000 s.

Figure 4. (a) Photon flux in the 100 MeV to 100 GeV band, derived from the LAT observations of GRB 160509A. The dashed line indicates the power-law fit $F_{\nu} \propto \nu^{1.06 \pm 0.13}$ for the LAT temporal decay from 40 s to 80 ks. The first and second emission episodes are also indicated. (b) Evolution of the photon index of the 0.1–100 GeV emission. (c) The photon flux in the 100 MeV to 1 GeV band. (d) The photon flux in the 1–100 GeV band. When there is no detection, the 90% confidence-level upper limits are shown.
Given the lack of simultaneous multi-wavelength observations, we only speculate on the possible origin of this soft emission. The simplest explanation can be synchrotron emission from the external shock electrons. A major issue with these is why it only dominates at a relatively short time period (300–1000 s) but not the whole GeV afterglow epoch (most of which is rather dominated by a hard spectrum). Though there is a huge gap of X-ray observations between the MAXI data at 330 s and XRT data at 7.2 ks, it is probably conceivable that the X-rays can be a combination of fast-decay, shallow decay/plateau, and/or X-ray flares between 330 s and 7.2 ks. Indeed, the second emission episode is seen during 280–420 s, so the central engine activity can last at least until ~420 s.

This extra soft component can also be a result of external inverse-Compton (EIC) processes (Wang et al. 2006; Galli & Piro 2007). In general, the peak energy of the IC emission and the seed photons are related by \( \varepsilon_{\text{p, IC}} \sim 2 \gamma_{\text{m}}^2 \varepsilon_{\text{seed}} \), where \( \gamma_{\text{m}} \) is the characteristic Lorentz factor of the forward-shock electrons, which (in the comoving frame) is given by \( \gamma_{\text{m}} = 1.8 \times 10^3 (p - 2)/(p - 1) \varepsilon_c (\Gamma_{\text{sh}} - 1) \) (Wang et al. 2006), where \( \varepsilon_c \) is the equipartition factor of electrons and \( \Gamma_{\text{sh}} \) is the Lorentz factor of the shock that accelerates the electrons, which can be about tens to several hundreds of seconds after the burst. Assuming typical shock parameters, Fan et al. (2008) predicted a delayed sub-GeV component caused by a UV/X-ray flare having a seed photon energy of 0.2 keV. While the peak time and duration of this observed soft component are roughly consistent with the EIC emission, a hypothetical UV/X-ray flare had to happen around 300 s after the burst onset. One may, however, speculate on the extrapolation of the second emission episode (t \( \sim \) 280–420 s) seen by the Fermi/GBM down to UV/X-ray energies. A major drawback of the EIC scenario is that there is no optical or X-ray observations at this time period; it is not possible to relate this additional component to any simultaneous X-ray activities. We do note that late central engine activities (e.g., X-ray flares) could have happened around this time, similar to many cases in other GRBs with early XRT observations (e.g., Yi et al. 2016). Indeed, X-ray flares were found to be temporally coincident with the LAT emission of GRB 100728A (He et al. 2012). The redshift of GRB 160509A, \( z \approx 1.17 \), put it at a distance whose very high energy emission could have been detected (Xue et al. 2009). Indeed, the detection of a 52 GeV photon (which arrived 77 s after the GBM trigger) and a 29 GeV photon (which arrived 70 ks after the burst) are consistent with most models of the extragalactic background light (EBL) at this redshift (e.g., see Figure 1 of Atwood et al. 2013 and references therein). This also verifies that an EBL correction on the multi-GeV spectrum for GRB 160509A is not important up to the highest energies we analyzed here. Having higher sensitivities at the low energy threshold of several tens of GeV, the upcoming Cherenkov Telescope array and LHAASO may be able to detect photons in the 10–100 GeV energy band during prompt and/or afterglow phases of a GRB. Simultaneous low-energy (e.g., X-rays, UV, optical) coverage is also crucial to discriminate the emission mechanism of these energetic photons.

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