GRB 210121A: A Typical Fireball Burst Detected by Two Small Missions

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Abstract

The Chinese CubeSat Mission, Gamma Ray Integrated Detectors (GRID), recently detected its first gamma-ray burst, GRB 210121A, which was jointly observed by the Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM). This burst is confirmed by several other missions, including Fermi and Insight-HXMT. We combined multimission observational data and performed a comprehensive analysis of the burst’s temporal and spectral properties. Our results show that the burst is relatively special in its high peak energy, thermal-like low-energy indices, and large fluence. By putting it to the $E_p-E_{iso}$ relation diagram with assumed distance, we found that this burst can be constrained in the redshift range of [0.3, 3.0]. The thermal spectral component is also confirmed by the direct fit of the physical models to the observed spectra. Interestingly, the physical photosphere model also constrained a redshift of $z \sim 0.3$ for this burst, which helps us to identify a host galaxy candidate at such a distance within the location error box. Assuming that the host galaxy is real, we found that the burst can be best explained by the photospheric emission of a typical fireball with an initial radius of $r_0 \sim 3.2 \times 10^{17}$ cm.

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

1. Introduction

The radiation mechanism that powers the prompt emission of gamma-ray bursts (GRBs) remains controversial. The leading two models, namely, the photospheric emission of the relativistic fireball not far from the central engine (Pe’er 2008; Zhang & Yan 2011; Geng et al. 2018; Hou et al. 2018; Meng et al. 2018, 2019; Zhang et al. 2018a) and the synchrotron emission of the Poynting flux of a magnetic outflow generated at a large radius (Zhang & Pe’er 2009; Zhang & Yan 2011; Zhang et al. 2016, 2018a), are both successful in reproducing some observed spectra on a burst-by-burst basis. The superposition of the thermal and the nonthermal components in some GRBs (Guiriec et al. 2011; Gao & Zhang 2015) further complicates the diversity and points toward a “hybrid” model. In this paper, we report a recent GRB 210121A, which contributes an additional smoking-gun case that puts strong evidence onto the photospheric emission origin.

GRB 210121A was detected by two small GRB missions recently launched in China. In particular, GRID is a low-cost student project aiming to build an all-sky and full-time CubeSat network in low Earth orbits in the energy range from 20 keV to 2 MeV (Wen et al. 2019), with a dedicated scientific goal of observing and accumulating a considerable large sample of GRBs. The first and second CubeSats of GRID were successfully launched in 2018 and 2020, respectively. To date, GRID has detected dozens of GRB candidates and one confirmed burst, GRB 210121A. Launched in 2020 December, GECAM (Peng et al. 2021) is a new Chinese high-energy astrophysics mission consisting of two microsatellites that aims to monitor all kinds of X-ray and gamma-ray transients in the energy range from about 6 to 5000 keV (Chen et al. 2020).

In this paper, we performed a comprehensive analysis of the high-energy data of GRB 210121A observed by multiple missions (Section 2). Motivated by its high peak spectral energy and unusually hard spectral indices, we further investigated how particular the burst is by comparing its temporal and spectral properties to those of a large GRB sample and by placing the burst on the $E_p-E_{iso}$ diagram (Section 3), and we showed that the photospheric model best
explains the burst. Our conclusions are further examined by a direct physical model fit (Section 4) and supported by a host galaxy candidate with appropriate redshift found in the location error box (Section 5). A brief summary is presented in Section 6.

2. Data Reduction and Analysis

GRB 210121A was detected by several other larger missions, including Fermi and HXMT. Fermi was launched in 2008, which comprises two scientific instruments, the Large Area Telescope (LAT; Atwood et al. 2009) and the Gamma-Ray Burst Monitor (GBM; Meegan et al. 2009) and covers a broad energy band from 8 keV to \(\sim 100\) GeV. The Hard X-ray Modulation Telescope (HXMT; Xue et al. 2021), Insight-HXMT, China’s first X-ray astronomy satellite, was launched in 2017 and consists of three main payloads, namely, the high-energy X-ray telescope (HE, 20–250 keV), the medium-energy X-ray telescope (ME, 5–30 keV), and the low-energy X-ray telescope (LE, 1–15 keV) (Li 2007; Zhang et al. 2018b, 2020b). However, the CsI detectors of HE can monitor the >100 keV gamma-ray sky unocculted by Earth. The measured energy range of CsI is 40–600 keV for Normal Gain mode and 200–3000 keV for low-gain mode (Luo et al. 2020). This study unitizes the high-energy data from all those telescopes, as well as the aforementioned GRID and GECAM missions.

2.1. Light Curves

GRB 210121A almost simultaneously triggered HXMT (2021-01-21T18:41:48.750 UTC; Xue et al. 2021) and GECAM (2021-01-21T18:41:48.800 UTC; Peng et al. 2021). For simplicity, we take a unique \(T_0 = 2021-01-21T18:41:48.800\) UTC and align all the data accordingly. The four-mission light curves, which are all binned with 0.2 s, are plotted together in Figure 1. The light curves are fully consistent with each other in the finest details, confirming the validation of the data of the four missions.

Following Yang et al. (2020b) and Yang et al. (2020a), we calculate the burst duration, \(T_{90}\), in the 8–800 keV energy band using the continuous time-tagged event (CTTE) data of the Fermi/GBM detector n0 with bin size = 0.064 s. The results are shown in Figure 2. With a \(T_{90}\) value of 13.31\(^{+0.22}_{-0.16}\) s (also see Table 1), GRB 210121A definitely belongs to the long GRB population.

We notice that several substructures are clearly present in the light curve. Guided by the Bayesian block methodology (blue histogram in the top panel of Figure 2; Scargle et al. 2013), we divided the burst into five main emission episodes at 0.05 effective significance level, as listed in Table 2, and performed spectral analysis for each of them in Section 2.3.
Table 1

| Observed Properties | GRB 210121A |
|---------------------|-------------|
| $T_{90}$ (sharp peak only) (s) | 13.31$^{+0.22}_{-0.16}$ |
| Total duration (s) | $\sim 16.31$ |
| $\alpha$ at peak | $-0.52^{+0.06}_{-0.05}$ |
| $E_{p}$ at peak (keV) | 1274.50$^{+192.64}_{-118.34}$ |
| Time-integrated $\alpha$ | $-0.59^{+0.02}_{-0.02}$ |
| Time-integrated $E_{p}$ (keV) | 954.33$^{+12.62}_{-3.84}$ |
| Total fluence$^c$ (10$^{-4}$ erg cm$^{-2}$) | 1.23$^{+0.08}_{-0.07}$ |
| Peak flux (10$^{-5}$ erg cm$^{-2}$ s$^{-1}$) | 2.19$^{+0.08}_{-0.06}$ |
| $z$ inferred by $E_{p} - E_{\text{iso}}$ relation | 0.3 – 3.0 |
| Nearest host galaxy candidate | J010725.95–461928.8 |

(z $\sim 0.319$)

Notes.

$^a$ All errors correspond to the 1σ credible intervals.

$^b$ The time-integrated spectral parameters are measured over the total duration.

$^c$ The total fluence and peak flux are calculated in the 10 keV–10 MeV energy band.

2.2. Spectral Lags

Spectral lag, attributed to the fact that higher-energy gamma-ray photons always arrive earlier than the lower-energy gamma-ray photons, is a common phenomenon in GRBs during their prompt emission epochs (Norris et al. 1986, 2000; Band 1997; Chen et al. 2005). Several physical models, such as the curvature effect of a relativistic jet and rapidly expanding spherical shell, have been proposed to explain the spectral lags (Ioka & Nakamura 2001; Shen et al. 2005; Lu et al. 2006; Shenoy et al. 2013; Uhm & Zhang 2016). Statistically speaking, long GRBs are always characterized by obvious spectral lags, whereas lags of short GRBs are always negligible (Norris et al. 1996; Yi et al. 2006).

To calculate the spectral lags, we first extract the light curves in different energy ranges from Fermi/GBM NaI detector n0 and BGO detector b0. The multiwavelength light curves are shown in Figure 3 (top panel). After selecting the main emission range of 0–12 s, we calculate the lags between the lowest energy and any other bands following the method in Zhang et al. (2012b). The results are shown in Figure 3 (bottom panel). A turnover presents at the lag versus $\Delta E$ plot, which has been noticed in some other long GRBs (e.g., Wei et al. 2017; Du et al. 2021).

2.3. Spectral Analysis

Both time-integrated and time-resolved spectral analyses are performed over the whole burst period, from $-0.01$ to 16.3 s. The five time-dependent slices, A to E, are obtained by the Bayesian block method as mentioned in Section 2.1 and illustrated in Figure 2. The photon flux in slice A is so bright that we can further divide them into five slices (A1–A5), each containing enough photon counts for spectral fitting. The boundaries of each slice are listed in Table 2.

For each slice, we extract the corresponding source and background spectra and the corresponding instrumental response files following the procedures described in Zhang et al. (2018a). Since the energy range of Fermi/GBM is the broadest one among the four missions, for simplicity we only employ the GBM data in our spectral analysis. The spectral data are obtained from three detectors with relatively small viewing angles (i.e., the NaI detector n0 and n3, as well as the BGO detector b0). Nevertheless, we have confirmed that the joint-mission spectral fitting (e.g., in Figure 4) using all four missions yields results consistent with those with GBM data only.

For each slice, we perform a detailed spectral fit using our self-developed Monte Carlo fitting tool McSpecFit (Zhang et al. 2016, 2018a) with five frequently used empirical models, namely, the band function (Band), the blackbody (BB), the multicolor blackbody (mBB), the single power-law (PL), and the cutoff power-law (CPL) models. $^7$ The ratio of Profile-Gaussian likelihood to the degree of freedom (PGSTAT/ dof; Arnaud 1996) and the Bayesian information criterion (BIC; Schwarz 1978) are taken into account to test the goodness of fit.

Our results show that the CPL model is the preferred one for all the time-resolved slices. The best-fit parameters obtained by the CPL models are listed in Table 2. The corresponding spectral evolution is plotted in Figure 5. The peak energy constrained by the CPL model is typically around 1 MeV throughout the burst and exhibits strong spectral evolution from slices A1 to A5. Some previous studies on multipulse long GRBs (e.g., Lu et al. 2012) found that the $E_{p}$ evolution displays two prevailing trends: (1) hard-to-soft then tracking, meaning $E_{p}$ first shows a hard-to-soft evolution at the beginning of the burst then tracks the intensity level; (2) the intensity-tracking, meaning $E_{p}$ tracking the intensity all the time during a burst. However, the $E_{p}$ evolution of GRB 210121A is different from neither of the two above. The $E_{p}$ follows the hard-to-soft pattern throughout the first pulse in slices A1–A5 and remains a high value until the final stage of the burst. The best-fit low-energy photon index, $\alpha$, evolves rapidly and tracks the flux level. Moreover, $\alpha$ systematically exceeds the synchrotron “death line” (Preece et al. 1998) defined by $\alpha = -2/3$ and reaches the highest value of $\sim -0.2$ in several slices, which indicates that the spectra are thermal-like (Meng et al. 2019).

The hard low-energy photon index motivates us to reevaluate the fit using thermal-like spectral models. Although the single blackbody model was unacceptable in the time-resolved spectral fit, we found that the multicolor blackbody model (mBB), on the other hand, can well explain the time-resolved spectra with adequate goodness of fit (Table 2). The corresponding best-fit values of $kT_{\text{min}}$ and $kT_{\text{max}}$ are also plotted in Figure 5.

3. Comparison Study

3.1. Comparison with Other Long GRBs

Based on above data analyses on GRB 210121A, we have obtained its temporal characteristic parameters such as $T_{90}$ and some spectral properties including the spectral...
Table 2

| ID  | Flux (10^{-4} erg cm^{-2} s^{-1}) | m | $E_{\text{peak}}$ (keV) | $E_{\text{rest}}$ (keV) | $E_{\text{iso}}$ (10^{52} erg) | BIC |
|-----|----------------------------------|---|--------------------------|--------------------------|-------------------------------|-----|
| A1  | 0.01                             | 0.43| 21.6±1.6                | 22.5±3.6                 | 55.3±10.0                    |     |
| A2  | 0.07                             | 0.47| 24.4±2.8                | 25.1±3.1                 | 85.0±10.0                    |     |
| A3  | 0.87                             | 0.52| 21.5±1.5                | 21.8±1.6                 | 55.6±10.0                    |     |
| A4  | 1.32                             | 0.76| 22.3±3.1                | 22.6±3.0                 | 60.7±10.0                    |     |
| A5  | 1.76                             | 0.97| 22.7±3.2                | 22.9±3.2                 | 61.2±10.0                    |     |
| A6  | 2.20                             | 1.12| 23.4±3.3                | 23.6±3.3                 | 62.2±10.0                    |     |
| A7  | 2.70                             | 1.27| 24.1±3.4                | 24.3±3.4                 | 62.9±10.0                    |     |

Note: The values in the table represent the spectral fitting results of GRB 210121A.
The Astrophysical Journal, 922:237 (10pp), 2021 December 1

Wang et al.

Table 3

| Parameter | Photosphere Model | Synchrotron Model |
|-----------|------------------|-------------------|
| \(\gamma_0\) | 789.82 +1051.91 -221.13 | log \(E_p\) | 3.94 +0.04 -0.01 |
| \(\rho\) | 4.92 +0.08 -1.26 | \(\rho\) | 5.99 +0.20 -0.20 |
| \(\theta_{\gamma,\text{inj}}\) | 0.02 +0.001 -0.01 | log \(\gamma_{\text{iso}}\) | 5.94 +0.04 -0.21 |
| \(\theta_{\gamma}\) | 0.02 +0.0002 -0.001 | log \(\frac{R_{\gamma}^0}{\gamma}\) | 4.81 +0.33 -0.55 |
| log \(\frac{L_0}{\text{erg s}^{-1}}\) | 51.94 +0.84 -0.50 | | 4.81 +0.33 -0.55 |
| log \(\frac{\Delta L}{\text{erg cm}^{-3}}\) | 7.51 +0.45 -0.46 | \(q\) | 1.56 +0.09 -0.17 |
| \(\zeta\) | 0.21 +0.05 -0.07 | \(b\) | 0.90 +0.03 -0.05 |
| BIC | 238 | PGSTAT | 424.1 |

3.2. Placement on \(E_p-E_{\gamma,\text{iso}}\) Correlation

The \(E_p-E_{\gamma,\text{iso}}\) relation (aka Amati relation; Amati et al. 2002) has been used as a powerful tool to diagnose GRB classifications. As shown in Figure 7, typical long and short GRBs follow two separate tracks. In addition, a third track was recently found for those short GRBs originating from magnetar giant flares (aka MGF GRBs; e.g., GRB 200415A, Yang et al. 2020a; Svinkin et al. 2021; Roberts et al. 2021; Zhang et al. 2020a). Since there is no redshift measurement for GRB 210121A, we assign its redshift as a free parameter ranging from 0.3 to 3.0 in order to be consistent with a long GRB. Other possibilities are almost ruled out, as it is certainly not a short GRB or a giant flare from a magnetar given the properties (e.g., nonnegligible lags, long duration) presented in Section 2. In addition, the absence of a nearby host galaxy at redshift \(\sim 0.0001\) further rules out its possibility of being an MGF GRB.

3.3. Constraints from Photosphere Death Line

As shown in Figure 7, GRB 210121A is a significantly extreme case among those GRBs with a redshift between 0.3 and 3.0. The large \(E_p\) value of GRB 210121A may be subject to the so-called “photosphere death line” constraints as discussed in Zhang et al. (2012a).

According to Zhang et al. (2012a), the photosphere emission model predicts an upper limit for the peak energy of a GRB in the form of

\[
E_p \leq \zeta L_{52} \approx 1.2 \xi \ell_{52}^{1/4} r_0^{-1/2} \text{MeV},
\]

where \(L_{52}\) is the luminosity in units of \(10^{52} \text{ erg s}^{-1}\), \(r_0\) is the initial fireball radius in units of \(10^7 \text{ cm}\), and the factor \(\xi\) is taken as 2.82 in this study, which invokes a relativistic multicolor blackbody outflow. Accordingly, with a known \(E_p\) and \(E_{\gamma,\text{iso}}\) owing to its significantly high peak energy and fluence in the whole long GRB sample.
one can calculate the lower limit of the initial fireball radius:
\[ r_0 \leq 1.44 \xi^2 \left( \frac{E_p}{\text{MeV}} \right)^{-2} \left( \frac{E_{\gamma,\text{iso},52}}{\Delta t} \right)^{1/2} \times 10^7 \text{ cm} .\] (2)

By putting the observed \( E_p = 1274.5 \text{ keV} , \Delta t = 0.44 \text{ s} , \) and flux of \( \sim 21.9 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \) into Equation (2), we obtain an upper limit for \( r_0 \) of
\[ r_0 \leq [3.10, 5.40] \times 10^7 \text{ cm} \] (3)
for a redshift range of \( z \sim [0.3, 3.0] \). Such an upper limit is fully consistent with the prediction of the standard fireball model (e.g., Mészáros & Rees 2000; Mészáros et al. 2002), as well as the mean acceleration radius \( (\sim 10^8 \text{ cm}) \) of the fireball derived from observed data (Pe’er et al. 2015).

4. Physical Models

This section employs two physical (photosphere vs. synchrotron) radiation models and fits them directly to the same observed data. By comparing the goodness of fit and parameter constraints of the two fits, we can, from the first principle, further evaluate the radiation mechanisms that shape the observed spectra.

4.1. Photosphere Model

We apply a structured jet photosphere model (Lundman et al. 2013; Meng et al. 2018, 2021) to fit the first-pulse spectra. The flux density of this model (in units of mJy) can be calculated numerically in the form
\[ F_{\nu}(E) = F_{\nu}(E; \eta_0, p, \theta_{c, r}, \theta_\eta, L_0, r_0, z). \] (4)

Seven parameters are involved, namely, the baryon loading value \( \eta_0 \), the power-law decay index of the baryon loading \( p \), the angular width for the isotropic core of the baryon loading \( \theta_{c, r} \), the viewing angle \( \theta_\eta \), the outflow luminosity \( L_0 \), the initial radius of the fireball \( r_0 \), and the redshift \( z \). As shown in Figure 8, the model successfully fits the data with a PGSTAT/ dof = 291.07/238.0 = 1.22. The best-fit parameters and their constraints as shown in Table 3 and Figure 9. The best-fitting value of the initial radius is \( r_0 = 3.2^{+2.7}_{-1.2} \times 10^7 \text{ cm} \), which is consistent with the constraints in Equation (3). Besides, the redshift is constrained to be \( 0.14 \leq z \leq 0.46 \).

The Lorentz factor at the photosphere can be discussed under two cases: saturated acceleration (Case I) and unsaturated acceleration (Case II). According to our results, the Lorentz factor is calculated to be
\[ \Gamma = \left\{ \begin{array}{l} \eta_0 \\ \sigma_T L(\theta) \end{array} \right\}^{1/3} = \begin{cases} 789.8, \text{ Case I,} \\ 405.4, \text{ Case II,} \end{cases} \] (5)
where \( \eta(\theta) = \frac{\eta_0}{(10/0.3)^2 + 1.2^2} + 1.2 \) is the structured baryon loading parameter and \( \theta \) is the angle measured from the symmetry axis of the jet. Assuming that the fireball is saturated accelerated and \( \theta = 0 \), the derived photosphere radius is \( R_{ph} = \left( \frac{3}{10 \xi^2} \right) \sigma_T L(\theta) \sim 1.0 \times 10^7 \text{ cm} \), compared with the saturated radius \( R_s = r_0 \eta(\theta) = 2.6 \times 10^7 \text{ cm} \), the result of which is inconsistent with the condition that \( R_s < R_{ph} \) in Case I. On the other hand, the Lorentz factor \( \Gamma = 405.4 \) is obtained precisely in Case II, which is consistent with the average \( \Gamma \sim 370 \) (Pe’er et al. 2015).

4.2. Synchrotron Model

Similarly, we apply the synchrotron model (Uhm & Zhang 2014; Zhang et al. 2016) to fit the same spectrum used in Section 4.1. The redshift is assumed to be \( z = 0.319 \) based on the constraints in Sections 3.2, 4.1, and 5. The flux density of this model (in units of mJy) is in the form
\[ F_{\nu}(E) = F_{\nu}(E; \Gamma, p, \gamma_{lim}, R_{lim}^0, q, B_0, b, \dot{\gamma}). \] (6)

Our fit can constrain eight parameters (Table 3, Figures 8 and 9): the Lorentz factor \( \Gamma \), the power-law index of the electron spectrum \( p \), the minimum Lorentz factor of electrons \( \gamma_{lim} \), the normalized injection rate of electrons \( R_{lim}^0 \), the power-law index
of the injection rate $q$, the initial magnetic field $B_0$, the decaying factor of the magnetic field $b$, and the time at which electrons begin to radiate in the observer frame $\hat{t}$.

Compared to the photosphere model in Section 4.1, the model is underfitting with a PGSTAT/dof = $424.10/237.0 = 1.79$. Besides, some of the parameters and the derived parameters are unreasonable:

1. The bulk Lorentz factor in this model is as high as 103.94, which is greater than the upper limit constrained in various ways (Racusin et al. 2011).
2. The photon index $\alpha = -(p-1)/2 = -2.5$. Not only is it inconsistent with the value in the CPL model, but also it is too soft compared to the typical values of the GRB sample (Poolakkil et al. 2021).
3. The emission radius, $R_0 = 2T_\gamma c^2 = 7.09 \times 10^{18}$ cm, appears to be too large as a GRB emission radius.

5. Host Galaxy Search

As shown in Section 4, the physical photosphere model constrains the redshift to a range of [0.14, 0.46]. Combining the Amati relation requirements (i.e., $z \sim [0.30, 3.0]$) in Section 3.2, we finally narrow down the redshift of GRB 210121A to [0.30, 0.46].

We then search the field of GRB 210121A for its possible galaxies within the redshift range of [0.30, 0.46]. There is no optical and X-ray counterpart observed for this burst. To get the localization, we make use of the Inter-Planetary Network (IPN) triangulation location of GRB 210121A, a $3\sigma$ error box of 181 arcmin$^2$ centered at R.A. = $16^{h}59^{m}58^{s}981$ and decl. = $-46^{\circ}24^{\prime}40^{\prime\prime}1$ (Hurley et al. 2021). Based on the public Konus-Wind data, this IPN error box is further improved by involving the joint triangulations of GECAM-Konus (Wind), HXMT-Konus (Wind), and GRID-Konus (Wind), as shown in Figure 10, which provides the final location box for the host galaxy search.

We searched four catalogs, namely, SIMBAD, NED, SuperCOSMOS, and HyperLeda, within that error box. Our

18 http://simbad.u-strasbg.fr/simbad/sim-fcoo
19 http://ned.ipac.caltech.edu
20 http://ssa.roe.ac.uk/WISExSCOS.html
21 http://leda.univ-lyon1.fr

Figure 5. The spectral evolution of the CPL model and mBB model. The horizontal errors represent the time spans, and the vertical errors indicate the $1\sigma$ uncertainties of the best-fit parameters. In the first panel, the red horizontal dashed line represents the synchrotron death line. The blue vertical dashed lines mark slice A.

Figure 6. Probability distributions of some characteristic properties of long GRBs. The red vertical dashed lines highlight GRB 210121A. The long GRB sample is from the Fermi/GBM catalog (Gruber et al. 2014; von Kienlin et al. 2014; Bhat et al. 2016; von Kienlin et al. 2020).

Figure 7. The $E_{pS}$ vs. $E_{\gamma,iso}$ correlation diagram. The black, pink, and purple solid lines are the best-fit correlations of the long, short, and MGF GRB samples. The green dashed line shows the trajectory of GRB 210121A by applying different redshift values, and the green points highlight some specific redshift values.

The Astrophysical Journal, 922:237 (10pp), 2021 December 1 Wang et al.
search yields only one galaxy, J010725.95−461928.8, in the SuperCOSMOS catalog, with \( \text{R.A.} = 16^\circ.858 \) and \( \text{decl.} = -46^\circ.325 \) and \( z = 0.319 \) (Bilicki et al. 2016), which is likely the host galaxy of GRB 210121A. We followed up the galaxy with the Las Cumbres Observatory (LCOGT) at 2021-05-09T04:01:16.593 UTC. The resulting image in the \( R \) band is shown in Figure 11. The host galaxy candidate is clearly visible. However, no optical counterpart for this GRB was detected in our observation.

6. Summary

After performing a comprehensive analysis of the high-energy data of GRB 210121A and the host galaxy search, we can claim the burst originating from the photosphere emission at a typical fireball radius due to the following rationale:

1. The burst is characterized by a hard low-energy spectral index, likely due to thermal origin.

Figure 8. The observed photon count spectra of the photosphere model and the synchrotron model.

Figure 9. Parameter constraints of the photosphere model (left) and synchrotron model (right) fit for the spectrum in the time interval of slice A.
2. To place the burst onto the long GRB track on the Amati relation, the large values of $E_p$ and fluence require a redshift range of $[0.3, 3.0]$.

3. The physical photosphere model successfully fits the observed spectra and constrains the redshift in the range $[0.14, 0.46]$.

4. By overlapping 2 and 3, one can further constrain the redshift to a range of $[0.30, 0.46]$.

5. By searching the error box of the GRB field, we only find one galaxy within the redshift range of $[0.30, 0.46]$. The galaxy is J010725.95$-461928.8$ at a redshift of 0.319, which is likely the host galaxy of the GRB 210121A.

6. With $z = 0.319$, one can derive the upper limit of the initial fireball radius by Equation (2), which gives $r_0 \leq 5.4 \times 10^{17}$ cm. Such an upper limit is fully consistent with the standard fireball model.

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**Figure 10.** The localization of GRB 210121A. The black quadrangle is the IPN error box. The green, blue, and red solid lines are $3\sigma$ error lines of joint localization of GECAM-Konus (Wind), HXMT-Konus (Wind), and GRID-Konus (Wind), respectively. The host galaxy candidate, J010725.95$-461928.8$, is marked with a blue star.

**Figure 11.** The follow-up observation on galaxy J010725.95$-461928.8$ with LCOGT. The left panel is the image of the area of sky near the localization of GRB 210121A. The middle panel is the area of sky localized in the error box constrained from Figure 10. The right panel is the host galaxy candidate J010725.95$-461928.8$. 

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