Measurement of the $\sim 10^{-16}$ Gauss inter-galactic magnetic field with high energy emission of GRB 221009A

Zi-Qing Xia,1 Yun Wang,1,2 Qiang Yuan,1,2 and Yi-Zhong Fan*1,2
1Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China
2School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, China
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The fast evolving TeV-PeV transients and their delayed GeV-TeV cascade emission in principle server as an ideal probe of the inter-galactic magnetic fields which are hard to be measured by other methods. Very recently, LHASSO has detected the very high energy emission of the extraordinary powerful GRB 221009A up to $\sim 18$ TeV within $\sim 2000$ s after the burst trigger. Here we report the detection of a $\sim 400$ GeV photon, without accompanying prominent $\gamma$ rays down to $\sim 2$ GeV, by Fermi-LAT in the direction of GRB 221009A at about 0.4 days after the burst. Such a hard spectrum is unexpected in the inverse Compton radiation of the electrons accelerated by the external forward shock. Instead, the inverse Compton scattering of the $e^\pm$ pairs, produced from the cascade of the early primary $\sim 20$ TeV $\gamma$ rays, off the diffuse far-infrared and microwave backgrounds can generate $\gamma$ rays up to $\sim 400$ GeV with a rather hard low energy spectrum. We infer that an inter-galactic magnetic field strength of $B_{\text{IGMF}} \sim 10^{-16}$ Gauss can naturally account for the arrival time of the $\sim 400$ GeV photon. Such a $B_{\text{IGMF}}$ is comparable to the limits set by the statistical studies of the high energy emission of TeV blazars.

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I. INTRODUCTION

The measurement of the inter-galactic magnetic field strength ($B_{\text{IGMF}}$), one of the fundamental parameters of the astrophysics that may be related to how the Universe starts/evolves and carries the information of the primordial magnetic fields [1, 2], is rather challenging. One promising method, initially proposed by Plaga [3], is to explore the arrival times of $\gamma$ rays from extra-galactic TeV transients such as Gamma-ray Bursts (GRBs [4–6]) and blazars [7, 8]. The basic idea is that, before reaching the observer, the primary TeV $\gamma$ rays will be absorbed by the diffuse infrared background and then generate ultra-relativistic $e^\pm$ pairs with Lorentz factors of $\sim 9.8 \times 10^5 (1 + z)(\epsilon_{\gamma}/1 \text{ TeV})$, where $z$ is the redshift of the source and $\epsilon_{\gamma}$ is the observed energy of the primary $\gamma$ rays. These pairs will subsequently scatter off the ambient cosmic microwave background (CMB) photons, and boost them to an average energy of $\epsilon_{\gamma, 2\text{nd}} \approx 0.8 (1 + z)^2 (\epsilon_{\gamma}/1 \text{ TeV})^2$ GeV. Unless $B_{\text{IGMF}}$ is very low (say, $\lesssim 10^{-20}$ Gauss), the presence of inter-galactic magnetic field will play the dominant role in delaying the arrival of the secondary $\gamma$ rays. Hence the observation of delayed $\gamma$-ray emission can in turn impose a tight constraint or give a direct measurement of $B_{\text{IGMF}}$ [3, 9, 10]. Such an idea has been firstly applied to the long-lasting MeV-GeV afterglow emission of GRB 940217 [3, 11, 12] and then to other GRBs, including for instance GRB 130427A and GRB 190114C [13, 14], two bursts with powerful very high energy $\gamma$-ray radiation [15, 16]. In these studies, the limits of $B_{\text{IGMF}} \gtrsim 10^{-21} - 10^{-17}$ Gauss have been set.

In this work we show that GRB 221009A, which is characterized by its huge power (the isotropic equivalent $\gamma$-ray radiation energy is $\sim$ quite a few $\times 10^{53}$ erg), low redshift ($z = 0.151$), and very strong TeV $\gamma$-ray emission [17–23], provides the community an unprecedented opportunity to probe the inter-galactic magnetic field. Using the Fermi-LAT detection of a $\sim 400$ GeV photon at $\sim 0.4$ days after the trigger, a $B_{\text{IGMF}} \sim 10^{-16}$ Gauss is derived.

II. FERMI-LAT DATA ANALYSIS

GRB 221009A triggered the Fermi Gamma-Ray Burst Monitor (GBM) on 2022-10-09 13:16:59 UT ($T_0$, MET 687014224), about 1 hour earlier than the Swift trigger [17, 18]. After 200 s of the Fermi-GBM trigger, the Fermi Large Area Telescope (LAT [24]) detected strong high-energy emission from GRB 221009A and the photon flux averaged in the time interval of $T_0 + 200 - T_0 + 800$ s is $\sim 10^{-2}$ ph cm$^{-2}$ s$^{-1}$ [21].

Here we focus on the long term of Fermi-LAT gamma-ray observations above 500 MeV in the direction of GRB 221009A (see also [25]). We select nearly one day ($T_0 + 0.05 - T_0 + 1$ day, MET: 687018224 - 687100624) of Fermi-LAT Pass 8 R3 data [26] after the Fermi-GBM trigger in the energy range of (500 MeV – 1 TeV) within 15 degrees from the Swift/UVOT localization (RA = 288.265°, DEC = 19.774° [17]) of GRB 221009A. The FRONT + BACK conversion-type data with the SOURCE event class are adopted in our work. We exclude LAT events coming from zenith angles larger than 90 degrees to reduce the contamination from the Earth’s limb and extract good time intervals with the recommended quality-filter cuts (DATA_QUAL=1 & LAT_CONFIG=1). To per-
form the analysis, we use the FermiTools package\(^1\) and the instrument response function P8R3\_SOURCE\_V3\(^2\) provided by the Fermi-LAT Collaboration. We use the make4FGLxml.py script to generate the initial model, which includes the galactic diffuse emission template (gll\_iem\_v07\_fits), the isotropic diffuse spectral model (iso\_P8R3\_SOURCE\_V3\_v1\_txt) and all the incremental Fourth Fermi-LAT source catalog [27] (gll\_psc\_v3\_fits) sources within 25 degrees. We model the \(\gamma\)-ray emission from GRB 221009A as a point source at the Swift/UVOT localization and set its spectral shape as the PowerLaw model.

We divide the data set into two time intervals of 0.05 – 0.3 day and 0.3 – 1.0 day after the Fermi-GBM trigger and carry out the unbinned likelihood analysis to optimize the model in each time interval, respectively. Because of the limited data, we only thaw the normalization and spectral index of GRB 221009A and normalizations of the Galactic diffuse and isotropic diffuse components in the fitting process. In the time interval of 0.05 – 0.3 day, GRB 221009A was well detected by Fermi-LAT with the photon flux of \((1.1 \pm 0.2) \times 10^{-6} \text{ph/cm}^2\text{s}\) and the spectral index of 2.08 \(\pm\) 0.19. This spectral index is anticipated in the synchrotron-self-Compton radiation model [5, 6]. While in the 0.3 – 1 day time interval, the data is dominated by a \(\sim\) 400 GeV photon arriving at 0.39 day after the Fermi-GBM trigger and there is just marginal evidence for the presence of emission around \(\sim\) 1 GeV. The photon flux is estimated to be \((3.3 \pm 3.1) \times 10^{-8} \text{ph/cm}^2\text{s}\) with a spectral index of 1.32 \(\pm\) 0.49, suggesting a significant flux decay and the emergence of a hard component. Then we calculate the spectral energy distributions (SEDs) for each time interval by separately fitting observations in 10 evenly spaced logarithmic energy bins from 500 MeV to 1 TeV. Here we fix the spectral index of GRB 221009A to 2 in each energy bin. The UpperLimits tool is adopted to calculate the 95% upper limit of the flux in the energy bin with a TS value \(<\) 9. The SEDs measured in these two time intervals and TS values for each energy bin are reported in Fig. 1.

In our analysis, the most important new finding is the detection of a 397.7 GeV photon, arriving at \(T_0+33554\) s. As shown in Fig. 2, the location of this amazing event is RA = 288.252° and Dec = 19.763° given by the red circle, which is nicely in agreement with the Swift/UVOT localization (the blue triangle, RA = 288.265° and DEC = 19.774° [17]) as well as that of LHAASO (the gold star, RA = 288.3° and Dec = 19.7° [23]). Pre-GRB 221009A, just two photon events larger than 100 GeV had been found in 14 years of Fermi-LAT observations within 0.5 degree of GRB 221009A, suggesting a rather low background level at energies above 100 GeV (One was observed with the energy of 268.1 GeV at the location of RA = 288.51° and Dec = 20.08°. The other 107.1 GeV photon was located at RA = 288.47° and Dec = 19.54°). Given its spatial and temporal coincidence with GRB 221009A, we conclude that this \(\sim\) 400 GeV photon is indeed physically associated with this monster. Then we calculate the probability that the LAT event belongs to GRB 221009A with the optimized model for the 0.3 – 0.1 day time interval with the gtsrcprob tool. It turns out to be 0.9999937, corresponding to a significance level of 4.4 \(\sigma\). Note that this \(\sim\) 400 GeV photon is among the ULTRACLEAN class events and the possibility for being a mis-identification of a cosmic ray is extremely low. Therefore, we have identified the most energetic GRB photon detected by Fermi-LAT so far. The previous records are a 95 GeV photon from GRB 130427A [15] and then a 99.3 GeV photon from GRB 221009A at an early time [19]. Because of the lack of strong accompanying GeV emission in the time interval of 0.3-1.0 day after the Fermi-GBM trigger, the detection of the single \(\sim\) 400 GeV photon likely points towards a hard low-energy spectrum. Indeed, the analysis of the Fermi-LAT data in the time intervals of 0.05 – 0.3 days and 0.3 – 1.0 days do reveal different spectral behaviors, indicating different physical origins (see Fig. 1).

III. INFEERENCE OF THE INTER-GALACTIC MAGNETIC FIELD

According to the LHASSO collaboration, the gamma-rays have been detected up to \(\sim\) 18 TeV [23]. At a redshift of 0.151, the optical depth (\(\tau\)) of the Universe to such energetic gamma-rays from interactions with photons of the intergalactic background light is quite high. Though the actual value is still not uniquely determined, it is widely be-

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\(^1\) https://github.com/fermi-lat/FermiTools-conda/
\(^2\) https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
believed that $\tau(z = 0.151, \epsilon_\gamma = 10 \text{ TeV}) > 5$ [28]. Consequently, most of the primary TeV gamma-rays should have been absorbed and newly generated $e^\pm$ have a Lorentz factor of $\gamma_e \approx 9.8 \times 10^8 (1 + z)(\epsilon_\gamma/10 \text{ TeV})$. The created ultra-relativistic $e^\pm$ particles would Compton scatter on ambient cosmic microwave background (CMB) photons to produce high-energy secondary gamma-rays with the average energy of

$$\epsilon_\gamma, 2\text{nd} \approx 80 (1 + z)^2 (\epsilon_\gamma/10 \text{ TeV})^2 \text{ GeV},$$

as long as the scattering is within the Thomson regime. Its arrival time is estimated to be [3, 9, 10]

$$t_{\text{arr}} \approx \max\{\Delta t_{\text{TeV}}, \Delta t_A, \Delta t_{\text{IC}}, \Delta t_B\},$$

where $\Delta t_{\text{TeV}}$ is the observed duration of the prominent TeV emission of the source, $\Delta t_A \approx 10 (1 + z)^{-1}(\epsilon_\gamma/10 \text{ TeV})^{-2}(n_{\text{IR}}/0.1 \text{ cm}^{-3})^{-1} \text{ s}$ is the angular spreading time delay (where $n_{\text{IR}}$ is the number density of the diffuse infrared background photons that governs the typical pair-production distance), $\Delta t_{\text{IC}} \approx 0.038 (1 + z)^{-6}(\epsilon_\gamma/10 \text{ TeV})^{-3} \text{ s}$ is the Inverse Compton (IC) cooling time delay, and the IGMF-induced pair deflection time is estimated as

$$\Delta t_B \approx 7 \times 10^5 \left(\frac{\epsilon_\gamma}{10 \text{ TeV}}\right)^{-5} \left(\frac{B_{\text{IGMF}}}{10^{-16} \text{ G}}\right)^2 \left(\frac{1 + z}{1.151}\right)^{-16} \text{ s},$$

where $B_{\text{IGMF}}$ is the strength of IGMF and the correlation length of the magnetic field is assumed to be larger than the IC cooling radius of the pairs ($R_{\text{IC}} \approx 2\gamma_e^2c\Delta t_{\text{IC}}/(1 + z) \approx 0.1 \text{ Mpc} (1 + z)^{-3}(\epsilon_\gamma/10 \text{ TeV})$).

In our re-analysis of the Fermi-LAT data, it is found out that at 33554 s after the Fermi-GBM trigger there came a gamma-ray with an energy of $\sim 400 \text{ GeV}$. Interpreting this event as the secondary inverse Compton photon discussed above, we would have

$$\epsilon_\gamma \approx 19 \left(\frac{\epsilon_{\gamma, 2\text{nd}}}{400 \text{ GeV}}\right)^{1/2} \left(\frac{1 + z}{1.151}\right)^{-1} \text{ TeV}.$$  

For the cascade emission of such energetic primary photons, both $\Delta t_A$ and $\Delta t_{\text{IC}}$ are negligible in comparison to $\Delta t_B$. Hence we measure the strength of IGMF as

$$B_{\text{IGMF}} \approx 1.2 \times 10^{-16} \left(\frac{\epsilon_{\gamma, 2\text{nd}}}{400 \text{ GeV}}\right)^{5/2} \left(\frac{\Delta t_B}{0.4 \text{ day}}\right)^{1/2} \left(\frac{1 + z}{1.151}\right)^{11/2} \text{ G}.$$  

Interestingly, this value is comparable with the lower limits set by the statistical investigation with a group of TeV blazars [29, 30]. In Fig. 3 we show the relationship between $\Delta t_B$ (supposing it dominates $\Delta t_{\text{arr}}$) and $\epsilon_{\gamma, 2\text{nd}}$ with this IGMF strength. If the intrinsic gamma-ray spectrum of the high energy emission of GRB 221009A extends up to $\sim 40 \text{ TeV}$, the cascade emission would be in TeV energies and might have already been detected by LHAASO (see the left part of Fig. 3). However, it may be somewhat challenging to robustly identify such a component because of the overlap with other TeV radiation component(s).

![FIG. 2: The $1^\circ \times 1^\circ$ Fermi-LAT counts map centered at the Swift/UVOT localization (i.e., the blue triangle) for the observations in the time interval of $T_0 + 0.05 - T_0 + 1$ day. The filled dots represent the Fermi-LAT events and the gold star marks the LHAASO localization reported in [23]. The 68% and 95% containment angles for Fermi-LAT at $\sim 400 \text{ GeV}$ [26] are also shown as red dashed and dot-dashed circular lines, respectively.](image)

![FIG. 3: The relationship between the IGMF-induced time delay $\Delta t_B$ and the average energy of secondary photons $\epsilon_{\gamma, 2\text{nd}}$, for the IGMF strength of $B_{\text{IGMF}} \sim 1.2 \times 10^{-16} \text{ Gauss}$. The observation periods by LHAASO and HAWC are also shown in shaded bands. The red circle marks the Fermi-LAT detection of the $\sim 400 \text{ GeV}$ photon from the direction of GRB 221009A.](image)
Though various inverse Compton radiation processes can generate GeV-TeV emission in the late GRB afterglow phase [31], the cascade emission of the prominent TeV transients is distinguished by its hard low energy spectrum as well as the soft high energy spectrum, as demonstrated both analytically [9] and numerically (see Fig. 1 of [10] though the $B_{\text{GRMF}}$ has been limited to be $\lesssim 10^{-18}$ Gauss; In particular, the higher the $B_{\text{GRMF}}$, the more quasi-monochromatic like the observed cascade gamma-ray spectrum). Such a feature is strongly favored by the current observations. On one hand, except the $\sim 400$ GeV gamma-ray, there is no confident detection of other photons with energies above 2 GeV in the direction of GRB 221009A in the time interval of 0.3 – 1.0 days after the GBM trigger, which suggests a hard low energy spectrum (see Fig. 1). On the other hand, HWAC started to observe this burst 8 hours after the trigger and obtained an upper limit of $\sim 7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ at 1 TeV by assuming a power law spectra with index of 2.0 [32]. Since this observation period overlaps with the Fermi-LAT detection of the $\sim 400$ GeV gamma-ray, the non-detection by HWAC is possibly due to several reasons. First, the intrinsic spectrum of the cascade secondary $\gamma$ rays may be rather soft at higher energies. As indicated by Eq. (2), the secondary TeV $\gamma$ rays, if there were, should have already arrived earlier (i.e., $\Delta t_{\gamma} \propto \epsilon_{\gamma,\text{2nd}}^{-5/2}$, see Fig. 3). Note that Eq. (1) is for the average energy of the IC photons and the highest energy can be larger by a factor of $\sim 3$. If the detected $\sim 400$ GeV photon is at the high end of the spectrum, then we would need $\epsilon_{\gamma} \sim 12$ TeV and $B_{\text{GRMF}} \sim 4 \times 10^{-17}$ G, which is about 1/3 of that obtained in Eq. (3). Second, the absorption of $\geq 1$ TeV photons by the diffuse infrared background is very efficient [28], and the effective area of HAWC at $\leq 400$ GeV is significantly smaller than that at TeV energies. Finally, the detection of the 400 GeV photon by Fermi-LAT is somewhat by chance, and the real flux is lower than the median value reported in Fig. 1. Assuming that the absorbed $\approx 20$ TeV photons have an intrinsic fluence of $\sim 10^{-5}$ erg cm$^{-2}$ (note that usually at such high energies, the spectrum would be significantly softer than the regular X-ray emission because of the Klein-Nishina suppression on the inverse Compton scattering [31]), the yielded $\sim 400$ GeV photons would have a flux of $\sim S/\Delta t_{\gamma} \sim 3 \times 10^{-10}$ (S/10$^{-5}$ erg cm$^{-2}$) erg cm$^{-2}$ s$^{-1}$, which is dimmer than the straightforward estimate with the Fermi-LAT 400 GeV photon detection in one day.

IV. SUMMARY

GRB 221009A is almost the most powerful gamma-ray bursts detected so far. Thanks to its rather low redshift $z = 0.151$, the emission has been detected up to about $\sim 18$ TeV. Because of the high optical depth of the universe to such energetic gamma-rays, the intrinsic spectrum likely extends to an even higher energy range and most of these primary photons have been absorbed by the far-infrared background before reaching us. The resulting ultra-relativistic $e^\pm$ pairs will up-scatter and then boost the cosmic microwave background photons to GeV-TeV energies. Motivated by such a prospect, we have analyzed the Fermi-LAT gamma-ray observations of GRB 221009A in the afterglow phase. In the time interval of 0.05 – 0.3 day, the high energy emission of GRB 221009A has been well detected in a wide energy range. While in the time interval of 0.3 – 1.0 day, the high energy emission is dominated by a 397.7 GeV photon arriving at 33554 s after the Fermi-GBM trigger and no other credible photons have been observed. Such facts strongly suggest different physical origins of the high energy emission in these two time intervals. In particular, the 0.3 – 1.0 day emission has a hard spectrum that is inconsistent with the model of the synchrotron-self-Compton radiation of the forward shock accelerated electrons. Instead, the electromagnetic cascade of $\sim 20$ TeV intrinsic $\gamma$-rays from GRB 221009A is a viable solution. The yielding $e^\pm$ pairs have a Lorentz factor of $\sim 2 \times 10^7$, and the delay of the arrival time of the secondary GeV-TeV photons is governed by the deflection of the $e^\pm$ pairs by the inter-galactic magnetic field. To account for a delay time of $\sim 0.4$ day, we need an inter-galactic magnetic field strength of $B_{\text{GRMF}} \sim 10^{-18}$ G, which is compatible with limits set by Fermi-LAT observations of TeV blazars [29, 30].

One prediction of our scenario is that LHASSO may have already detected the cascade secondary TeV emission if the intrinsic spectrum of the high energy emission of GRB 221009A extends up to $\sim 40$ TeV (see Fig. 3). The overlap with the TeV emission from other physical process(es) however may render the identification of the cascade component a bit challenging.

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