Understanding of the Brightest-of-all-time GRB 221009A

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Outline

• Introduction to GRB and GRB 221009A

• LHAASO observations of GRB 221009A

• A two-component jet model for the multi-wavelength afterglows

• Discussions
GRB emission includes two stages: prompt emission + afterglow.
GRB 221009A: brightest-of-all-time (BOAT)

- Triggered on a weak precursor by Fermi
- Fluence: $>0.05 \text{ erg/cm}^2$, at low redshift ($z=0.151$)
- Brightest-of-all-time (BOAT GRB)

Fermi/GBM

Main burst cause pile-up

GECAM/Konus-Wind Observations of GRB 221009A

An et al. 2023

- Not saturated, Fluence~ 0.2 erg/cm², $E_{\gamma,\text{iso}} \sim 1.5 \times 10^{55}$ erg

Buns et al. 2023
GRB 221009A: A very rate event

Fluence: $F \sim D^{-2}$

Event rate: $R \sim D^3$

Its fluence is 50 times higher than the 2nd brightest GRB

Event rate: $R < 10^{-3}$ yr

A Chinese song: “千年等一回”
“waiting a thousand years for once”
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The Electromagnetic Spectrum

Wavelength in Metres

Electron Volts (eV)

Relative Wavelength Size

Spectrum

Sources

TeV energy

Radio Waves

Microwaves

Infrared

Visible Light

Ultraviolet

X-rays

Gamma Rays

AM/FM Radio

Microwave Oven

People and Other Living Things

The Sun

X-Ray Machines

Radiotherapy Machines

Very-high Energy Cosmic Source

Image credits: Vecteezy.com, Drogenarto.net, NIKO, WEL, CERN, NASA
TeV observations of GRBs: decaying afterglows

Magic coll. 2019a, Nature

HESS coll. 2019, Nature

HESS coll. 2021, Science
How about TeV emission before deceleration?

- TeV emission during the coasting phase?
- Any TeV emission during the prompt emission?

✓ IACTs are pointed instruments that need time to slew to the GRB

✓ Extensive air shower detectors allow observations during the prompt GRB and the afterglow onset, but no detection yet
LHAASO

Location: Shichuan, China  
Altitude: 4410 m

A dual-task facility designed for \(\gamma\)-ray and CR studies:

1) **KM2A**: Kilometer Square Array  
2) **WCDA**: Water Cherenkov Detector Array  
3) **WFCTA**: Wide Field-of-view Cherenkov Telescope Array
LHAASO Observations of GRB221009A

- GRB 221009A occurred within the FOV of LHAASO: first GRB seen by an extensive air shower detector

- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)

- TeV light curve: a rise to peak after a quiescent phase, then a decay

LHAASO Collaboration, Science 380, 1390 (2023)
MeV vs TeV light curves: external shock origin

- Smooth temporal profile suggests it is a TeV afterglow
- First time detection of the onset of a TeV afterglow!
Afterglow starting time: $T^*$

- Triggered on a weak precursor
- measuring times from the beginning of the main burst emission (Kobayashi & Zhang 2007):
  \[ T^* \approx 225 - 228 \text{ s} \]
- Fitting of LHAASO light curve:
TeV light curves: 4-segment power-law

- Count-rate light curve
- Energy flux light curve

LHAASO Collaboration, Science 380, 1390 (2023)
1. Rising phase

- Fast rise: $\alpha_0 = 14.9^{+5.7}_{-4.0}$
- Slow rise, coasting phase
  $\alpha_1 = 1.82^{+0.21}_{-0.18}$
- Expected light curve: $t^2$ agrees with $k=0$ (ISM), inconsistent with $k=2$ (stellar wind)
  \[ n \propto R^{-k} \]
- Rapid rise is unusual, possibly due to energy injection

LHAASO Collaboration, Science 380, 1390 (2023)
The initial bulk Lorentz factor $\Gamma_0$

- From $T^*$ to the peak, it takes $\sim 18$ s
- The bulk Lorentz factor is estimated as

$$\Gamma_0 = \left( \frac{3E_k}{32\pi n m_p c^3 t_{\text{peak}}^3} \right)^{1/8} = 440 E_{k,55}^{1/8} n_0^{-1/8} \left( \frac{t_{\text{peak}}}{18 \text{ s}} \right)^{-3/8}$$

it is among the highest values for all GRBs
2. decay phase

\[ \alpha_2 = -1.115_{-0.012}^{+0.012} \]

\[ \alpha_3 = -2.21_{-0.83}^{+0.30} \]

\[ T_{b,2} = T^* + 670_{-110}^{+230} \text{s} \]

Revealing a jet break at the earliest time.
A narrow GRB jet

• Light curve steepens when the increasing radiation cone exceeds the jet opening angle
• Jet breaks have been seen in optical/X-ray bands
• An early jet break implies a narrow jet:

\[ \theta_0 \sim 0.6^\circ E_{\gamma,55}^{-1/8} n_0^{1/8} \left( \frac{t_{b,2}}{670 \text{s}} \right)^{3/8} \]

• Lead to a normal beaming-correct energy

\[ E_{\gamma,j} = E_{\gamma,\text{iso}} \theta_0^2 / 2 \sim 7.5 \times 10^{50} \text{ erg} E_{\gamma,\text{iso,55}}(\theta_0/0.7^\circ)^2 \]

Frail et al. 2001
Multi-wavelength modelling

afterglow synchrotron + SSC (first $10^4 \text{s}$)

- X-ray: synchrotron
- GeV: synchrotron + SSC
- TeV: SSC

One possible solution: $\tilde{E}_k = 1.5 \times 10^{55} \text{ erg}, \Gamma_0 = 560, \epsilon_e = 0.025, \epsilon_B = 6 \times 10^{-4}, p = 2.2, n = 0.4 \text{ cm}^{-3}$ and $\theta_0 = 0.8^\circ$.

LHAASO Collaboration, Science 380, 1390 (2023)
An inner jet is insufficient

- Late afterglows need outer, wider components
- Implying a structured jet

See also O'Connor et al. 23; Gill & Granot 23; Sato et al. 23

Numerical simulation by Gottlieb et al. 2021
GRB 221009A: seeing the brightest core of a structured jet

- The “core” of a nearby GRB is revealed
- Explain the unprecedently large fluence
- Low chance probability
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A two-component jet model


\[
\epsilon \equiv \frac{dE}{d\Omega} = \begin{cases} 
\epsilon_I, & \theta < \theta_j, \\
\epsilon_{II} f(\theta), & \theta_j < \theta < \Theta
\end{cases}
\]

\[
f(\theta) = \left[ \left( \frac{\theta}{\theta_{c,w}} \right)^{2a_1} + \left( \frac{\theta}{\theta_{c,w}} \right)^{2a_2} \right]^{-1/2},
\]
A STRATIFIED DENSITY PROFILE

- Transition from constant-density medium to wind-like medium

LHAASO data: $n_0 \geq 0.1 \text{cm}^{-3} E_{I,\text{iso},55}^{-(9-p)/(21-p)} \epsilon_B^{-2/(7-p)}$. 

$n_0 \leq 0.007 \text{cm}^{-3} E_{II,\text{iso},54}^{-(3-p)/(7-p)} \epsilon_B^{-2/(7-p)}$.

$n(r) = \begin{cases} n_0, & r < r_c \\ Ar^{-2}, & r \geq r_c \end{cases}$
A two-component jet model
A two-component jet model with sideways expansion

- Assuming side expansion for the narrow jet
- Fit to the GeV data is improved
- But the radio flux exceed the data by a factor of ~2
Considering the time-varying microphysical parameter: a decreasing acceleration fraction?

- Decreasing $k_e$ is required by the data

\[ k_e = \epsilon_e / \xi_e \]

- Decreasing Acceleration Fraction $\xi_e$

\[ \xi_e \propto t^{-\alpha \xi} \]

\[ F_{\nu} \propto \begin{cases} t^{2(3\nu - 1) - \alpha \xi}, & \nu < \nu_m \\ t^{2(3\nu - 1) - \alpha \xi(p-1)} + \alpha \xi(p-2), & \nu_m < \nu < \nu_c \\ t^{2(3\nu - 2) - \alpha \xi(p-2)} + \alpha \xi(p-2), & \nu > \nu_c \end{cases} \]

- Or increasing $\epsilon_e$
Decaying Magnetic Field model

• standard afterglow shock model assume a homogeneous magnetic field in the
downstream of the shock.

• Nonetheless, the realistic magnetic field may have a spatial distribution behind the
shock: decaying with the distance from the shock front (Lemoine et al. 2013)

\[ \alpha_t = \frac{\log[\epsilon_{B-}/\epsilon_{B+}]}{\log[t_{dyn}/\tau_{\delta B}]} \]

\[ -0.5 \lesssim \alpha_t \lesssim -0.4. \]

• Radio-emitting electrons may radiate most of their energy at the back of the blast
wave, where the magnetic field has decayed to a low value (Lemoine 2013; Wang
et al. 2013).
Discussion: 1) origin of ~10 TeV photons

- Klein-Nishina effect leads to a spectral steepening in SSC emission
- KM2A detected 3-13 TeV photons
- > 3 TeV emission needs a new component
  - Reverse shock proton synchrotron emission (Zhang et al. 2023)
  - UHECR propagating in IGM (e.g., Das & Razzaque 2023)
  - An extra hard electron component

--Can GRB produce UHECRs?
Proton synchrotron emission: TeV afterglow emission

Hybrid Emission Modeling of GRB 221009A: Shedding Light on TeV Emission Origins in Long-GRBs

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**Discussion: 2) prompt TeV emission limit**

- The most strict limit on the prompt TeV emission
  \[ R = \frac{F_{\text{TeV}}}{F_{\text{MeV}}} < 2 \times 10^{-5} \]

- If MeV emission arises from synchrotron emission, where is the IC emission?

- Internal \( \gamma\gamma \) absorption leads to an exponential cutoff?
  \[ \gamma\gamma \rightarrow e^+e^- \]
A Poynting-flux-dominated jet?

**But**, internal shock simulations result in a broken power-law spectrum (Aoi et al. 2010; Dai et al. 2023)

Then, we need a low ratio between SSC and synchrotron emission outputs.

Implying the magnetic field energy density is much larger than the electron energy density: $\epsilon_B \gg \epsilon_e$

A Poynting-flux-dominated jet suppress the SSC emission?

Conclusions

1. First time observing the onset of a GRB TeV afterglow
   This enables
   ① Estimating the initial bulk Lorentz factor $\Gamma_0$ of the jet
   ② Setting the most strict limit on the prompt TeV emission (a Poynting-flux-dominated jet?)

2. Finding a jet break in the TeV light curve in its decay phase
   ① The narrowest jet of $0.8^\circ$, revealing the “core” of a structured jet
   ② The unprecedently large fluence may be due to seeing the brightest core of a nearby GRB jet

3. A two-component jet model can explain the multi-wavelength data, and may requires time-varying microphysical parameters.