GRB 190114C and Multipolar Neutron Star

Yu Wang

ICRANet / INAF / University of Rome

July 1st, 2019, ICRANet, Pescara
In the past 50 years, gamma-ray burst (GRB) has been one of the main focuses of astrophysical research. Its phenomena have been complemented gradually by two paths.

1. New generations of satellites expand the observational capacity.

2. Specific GRBs carry rich or/and characteristic information.
INTRODUCTION
First Path: New Generations of Satellites

1. Vela detected the first GRB on July 2, 1967.

2. BeppoSAX confirmed GRB’s cosmological origin with the first redshift measurement, and discovered the first afterglow.

3. Swift broadened the observations in number and in great detail.

4. Fermi made possible to analyse the GeV spectrum.
1. GRB 980425 revealed the GRB and supernova association.

2. GRB 090902B exhibits thermal domination.

3. GRB 130427A brought the unprecedentedly abundant and long-lasting GeV observation.

4. GRB 130603B displayed the kilonova signal.

5. GRB 170817A coincided with the gravitational wave event.
INTRODUCTION
GRB 190114C Combines Both Paths

*First Path*: MAGIC telescope highlights the fast follow-up observation of GRBs in its science program since its inception, and TeV photon was eventually found in GRB 190114C.

*Second Path*: GRB 190114C epitomises the specific GRBs features, that the strong and long duration GeV emission, the high thermal abundance, and the representative broad spectral evolution, together with its characteristic TeV emission, GRB 190114C presents to us the most complete portrait of a GRB hitherto.
GRB 190114C caught great attention of the astronomical society, more than 30 instruments contributed to the observation, and some observations are still going on.

**High energy:** MAGIC, Fermi-LAT;

**Gamma-ray:** Fermi-GBM, SPI-ACS/INTEGRAL, AGILE/MCAL, Konus-Wind;

**Soft and hard X-ray:** Swift-BAT, Swift-XRT, Insight-HXMT/HE;

**Ultraviolet, optical and infrared:** MASTER, VLT/X-shooter, Pan-STARRS, NOT, OASDG, GROND, GTC, McDonald Observatory, SNU Observatory Swift-UVOT, Mondy, REM, LSGT, GRowth-India, KMTNet, UKIRT, CHILESCOPE, HCT, NTT, COATLI, RATIR, RTT150;

**Millimeter, submillimeter and radio:** ALMA, SCUBA-2, VLA, ATCA, RT-22, SRT, MeerKAT, GMRT.
The bore-sight angle (the angle between the GRB 190114C and the Fermi-LAT bore-sight) of Fermi-LAT, as well as the time coverage of Fermi-LAT, Swift-XRT and MAGIC.

The green curve is the evolution of the bore-sight angle since the trigger.

The grey shades cover the good time intervals of the Fermi-LAT observation. The blue shadow and the grey dots correspond to the observation time of Swift-XRT and MAGIC.

There exists a common time interval from $\sim 50$ s to $\sim 200$ s covered by Fermi and MAGIC, as well as partially covered by Swift and other lower energy telescopes.
Test Statistics (TS) of GRB 190114C and other 138 GRBs observed by Fermi-LAT. There are 9 GRBs with significant TS > 500. We consider the photon energy form 100 MeV to 100 GeV within T90, from 0 – 116 s, A TS value of 2520 is obtained.
The Fermi-LAT photons in the first 500 s. Upper: the count rate light-curve for photons of energy 100 MeV to 100 GeV. Lower: the energy of each single photon and its arrival time. Grey, red and blue colours represent < 50%, > 50% and > 80% of the probability that this photon belonging to the GRB 190114C. After 250 s, there is no photon having high probability > 80%.
Count light-curve of Fermi-GBM. This plot covers the entire T90 of $0 - 116$ s. The background is fitted by the green line. The orange shadow denotes the two pulses.
Bayesian Monte Carlo fitting of Fermi-GBM spectrum from 0 s to 116 s (T90).

We apply 20 chains, each chain iterates 104 times and burns the first 103 times.

The parameters are normalisation (Norm CPL), cut-off energy (1230 keV) and power-law index (-1.323) of the cut-off power-law model, as well as normalisation (Norm BB) and temperature (kT=132 keV) of the blackbody model.
Multi-wavelength spectrum from 0 to 116 s (T90). The spectrum includes data from Fermi-GBM (4 NAI and 2 BGO detectors) and Fermi-LAT. The fitting of Fermi-GBM is presented by a solid line, including the components of a blackbody function in dashed line and a cutoff power-law in dotted line. The Fermi-LAT data as blue crosses are fitted by a power-law function as dash-dot line. The extrapolation of Fermi-LAT fitting connects the Fermi-GBM data.
Similar evolution of GRB 190114C and 130427A.

The x-axis is the rest-frame time of GRB 190114C, the time of X-ray, gamma-ray and GeV light-curves of GRB 130427A $t$ are scaled by a linear transformation

$$t' = 0.53 \times (t - 2.23) \text{ s.}$$

The y-axis is the luminosity, we arbitrarily shift the three light-curves, they all overlap.

These two GRBs generally have the same behaviour after the rescaling, they infer the same system configuration with different scales.
The solid line is the fitting of the lower boundary of the data points; dashed line corresponds to the linear relation of LIV time delay ($A = 0.032$ is obtained from the LIV constrain $E_{\text{QG}} = 0.63 \times 10^{16}$ GeV) inferred from the time lag of Fermi-LAT spectra.

The solid line of the lower boundary may present the initial photons, by extrapolating the solid line, a 100 GeV photon is supposed to arrive at ~20 s, and the first 1 TeV photon may arrive at ~35 s.
In some theories of quantum gravity, the energy of a photon has a dispersion relation due to the Lorentz invariance violation.

A Taylor series expansion presents the energy of a photon, the leading term reads

\[ E^2 \approx p^2 c^2 \left[ 1 - s_\pm \left( \frac{pc}{E_{QG,n}} \right)^n \right] \]

where \( p \) is the photon momentum, \( c \) is the constant speed of light, and \( E_{QG} \) is an effective quantum-gravity energy scale, \( n \) indicates the order of expansion, \( s = \pm i \) signifies the positive or negative affection from the change of photon momentum. Therefore, the propagation speed of a photon depends on its energy

\[ v = \frac{\partial E}{\partial p} \approx c \left[ 1 - s_\pm \frac{n + 1}{2} \left( \frac{E}{E_{QG,n}} \right)^n \right] \]

Considering Two photon with higher energy \( E_h \) and lower energy \( E_l \) have different velocities. If they are generated at a same moment at redshift \( z \), taking into account the cosmological expansion, they will arrive at us with a time delay

\[ \Delta T_{LIV} = - \frac{1 + n}{2H_0} \frac{E_h^n - E_l^n}{E_{QG,n}^n} \int_0^z \frac{(1 + z')^n dz'}{\sqrt{\Omega_m(1 + z')^3 + \Omega_{\Lambda}}} \]

HIGH-ENERGY PHOTON DELAY

Possible Reason 1: Lorentz Invariance Violation

First, we adopt the spectral time delay of 3.25 s to constrain the effective energy scale $E_{QG,n}$

We obtain, at redshift $z = 0.42$, for the linear correlation ($n = 1$)

$$E_{QG,1} > 0.63 \times 10^{16} \text{ GeV}$$

and for the quadratic correlation ($n = 2$)

$$E_{QG,2} > 3.4 \times 10^7 \text{ GeV}$$

This result is consistent with the constraints from the spectral delay of GRB 160625B (J. J. Wei and et al 2017)
Second, we try to infer the constraint by the arriving time of single photons.

High energy photons associated to GRB 190114C with probability more than 50% infers a general feature that the higher energy photons come later.

If we assume the photons on the lower boundary are all originated in the initial first second, we relate the difference of the arriving time to the LIV, then we obtain the a phenomenological formula for the LIV by the fitted function of the lower boundary. The solid line presents such a fitted function,

\[ T = 0.35 \left( \frac{E}{\text{MeV}} \right)^{1/3} + 0.5 \text{ s} \]

The index of \( 1/3 \) differs from the usual dispersion law of equation as a Taylor expansion with power index \( > 1 \).
The time of a photon with energy $E$ escapes the outflow is approximately determined by its time of transparency $\Delta T(E)$, which is related to the radius of transparency $R_T(E)$, assuming this radius is much larger than initial radius and the photo-spherical radius, and assuming the bulk Lorentz $\Gamma \propto R^a$, we have

$$\Delta T(E) = \int_0^{R_T(E)} \frac{1}{2c\Gamma^2} dR \propto R_T(E)^{1-2a}$$

$R_T(E)$ can be obtained by equating the opacity to unit

$$\Gamma^{-2} \int_{E_{th}(E)}^{\infty} \sigma(E)n(E, R_T)R_T(E)dE = 1$$

considering a power-law spectrum, the count flux density $n(E, R) \propto R^{-2}E^b$, we obtain

$$R_T(E) \propto E^{\frac{b+1}{2ab-1}}$$

the transparency time finally is given as a function of photon energy

$$\Delta T(E) \propto E^{\frac{b-2a}{2ab-1}-1}$$

we attribute this transparency time as the time delay of GeV photon with energy $E$. 

**HIGH-ENERGY PHOTON DELAY**

Possible Reason 2: Time of Transparency
Possible Reason 2: Time of Transparency

\[
\Delta T(E) \propto E^{b-2a}_{2ab-1} - 1
\]

Taking the averaged photon index \( b = -2.09 \) from the Fermi-LAT observation of 3 s to 10 s, and the time delay relation \( \Delta T(E) \propto E^{1/3} \) found in the GeV photons delay, we obtain the acceleration index \( (\Gamma \propto R^a) \)

\[ a = 0.21 \]

From the theory, different compositions of the relativistic outflow lead to diverse evolution of the Lorentz factor \( \Gamma \):

- **radiation dominated scenario**, \( \Gamma \propto R \) \((a = 1)\)
- **matter dominated scenario**, \( \Gamma \) is a constant \((a = 0)\)
- **Poynting flux dominated scenario**, \( \Gamma \propto R^{1/3} \) \((a = 1/3)\).

None of the three compositions of outflow conforms to the observation, as well as the LIV effect. A realistic scenario may occur in the transitional phase of many compositions, or it conjugates several effects.
Luminosity light-curve of Fermi-GBM (MeV, Orange), Fermi-LAT (GeV, Green), Swift-XRT (X-ray, Grey).

The red region is the estimation of the intrinsic luminosity in the MAGIC energy band at energy 300 GeV to 10 TeV from 50 s to 1200 s, extrapolating the Fermi-LAT afterglow data.

It is also possible that a TeV bump exists before 100 s, with luminosity 1-2 orders of magnitude higher than the red region, by assuming the prompt emission contains TeV emission and the TeV photons follow a time delay as the GeV photons.
Fitting of Fermi-LAT light-curve by the locally weighted regression. The total energy of Fermi-LAT is obtained by integrating the solid line, the shadow is the 1-sigma uncertainty region.
The resultant energy from Fermi-LAT in the energy range of 100 MeV to 100 GeV is $1.8 \pm 1.3 \times 10^{53}$ erg, equivalent to $\sim 75\%$ of its gamma-ray isotropic energy, which previously was considered as the majority of a GRB’s energy, of $2.47 \pm 0.22 \times 10^{53}$ erg released in the energy range of 1 keV to 10 MeV.

Extrapolating the spectrum obtained from Fermi-LAT to a wider energy range of 10 MeV to 1 TeV, within which the total energy is more than $3 \times 10^{53}$ erg.
On one hand, GRB 190114C owns the most complete features of a GRB ever: from the viewpoint of components, it shows a complete structure from the prompt emission, afterglow to the emergence of supernova; from the viewpoint of radiation, it presents multi-wavelength emissions from radio, optical, X-ray, gamma-ray till TeV, it possesses both significant thermal and non-thermal photons, and its spectrum exhibits wide-range variation.

On the other hand, more than 30 satellites and telescopes participate the observation, which is one of the largest observational campaigns for GRBs.

The fusion of the above immanent cause and external cause makes GRB 190114C unique and general.
NEUTRON STAR

Multipolar Neutron Star Born in Gamma-ray Burst
I. A highly magnetized neutron star (NS) can be generated during the Gamma-ray burst (GRB), and it affects the evolution of afterglow.

II. High-order multipoles are required by many NS observations, they are relatively prominent in fast-spinning NS, as the newborn NS.
Multipolar Emission

The electromagnetic field of neutron star (NS) is described by the vector spherical harmonics. Each harmonic mode is identified by a set of multipole order number \( l \) and azimuthal mode number \( m \). Including dipole \((l=1)\), quadrupole \((l=2)\), hexapole \((l=3)\), octopole \((l=4)\) and high-order poles.

Neutron Star losses its rotational energy by emitting Poynting flux, the spin-down luminosity of each magnetic pole (order \( l \)) is

\[
L_l = - C_l \Omega_l^{2l+2} B_l^2 R^{2l+4} \Theta_l^2
\]

where \( C_l \) is a constant, \( B_l \) is the magnetic field, \( R \) is the radius of the NS, \( \Theta_l \) is the angular term related to azimuthal number \( m \). The time evolution of the angular velocity and the luminosity for a single mode are

\[
\Omega = \Omega_0 (1 + \frac{t}{\tau_l})^{-2l} \quad L_l = L_{l,0} (1 + \frac{t}{\tau_l})^{-1-1/l}
\]

The characteristic timescale and the initial luminosity are

\[
\tau_l = \frac{I \Omega_0^{2l+1}}{(2l+2)C_l \Omega_0^{2l} B_l^2 R^{2l+4} \Theta_l^2} \quad L_{l,0} = \frac{I \Omega_0^2}{2l \tau_l}
\]

where \( \Omega_0 \) is the initial angular velocity, \( I \) is the momentum of inertia.
MULTIPOLAR NEUTRON STAR BORN IN GAMMA-RAY BURST

Emission of a Single Multipole

The highest spin-down luminosity of different multipoles with the same magnetic strength ($B \sim 10^{14}$ G).

All the modes have a plateau phase, followed by a power-law-like decay, the higher mode multipole produces a shadower decay.
In reality, multi-modes may exist in a newborn NS, its luminosity is obtained by solving

\[ L = -I\Omega\dot{\Omega} = \Sigma L_l \]

Figure shows a NS having dipole, quadrupole and hexapole simultaneously.

Before one year \((3 \times 10^7 \text{ s})\), the high-order poles dominate the energy release, then the dipole starts to be dominant. In other words, the multipolar modes are important in a newborn NS, and for most of the NSs we observe today, the dipole contributes the majority emission.
MULTIPOLAR NEUTRON STAR BORN IN GAMMA-RAY BURST

Powering GRB Afterglow

NS spin-down energy powers the GRB afterglow. The multipolar model is able to fit the plateau and the normal decay, since the multipoles could inject energy (spin-down luminosity) in a wider range of power-law decay indices (-2 to -1).

Give the initial spin period \( (P_0) \) and the magnetic field components. The majority of GRB afterglows indicate the fast spinning newborn NSs evolve high-order poles, mainly the quadrupole.
THANK YOU