THE MAXIMUM ISOTROPIC EQUIVALENT ENERGY OF GAMMA RAY BURSTS

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ABSTRACT

The cannonball model, which unifies cosmic ray bursts (CRBs) and gamma ray bursts (GRBs), is used to predict the maximum isotropic equivalent gamma ray energy release in a GRB. The predicted maximum is based on the observed knee around 1 TeV in the energy spectrum of Galactic cosmic ray electrons, and on the Amati correlation in GRBs. Both were predicted by the cannonball model of CRBs and GRBs before their empirical discoveries. The predicted maximum agrees well with that concluded from up-to-date GRB observations.
1. INTRODUCTION

Gamma ray bursts (GRBs) are the most luminous sources of electromagnetic radiation in the observable universe (Fishman & Meegan 1995). They were first detected on July 2, 1967 by the USA Vela spy satellites, which were launched to detect possible USSR tests of nuclear weapons above the atmosphere, in violation of the USA-USSR Nuclear Test Ban Treaty signed in 1963. Their discovery was first published in 1973 after 15 such events were detected (Klebesadel et al. 1973), which have ruled out man-made origin and indicated that they were outside the solar system.

Until 1991, it was widely believed that the observable GRBs are located in our Galaxy. But, shortly after its launch in 1991, the Compton Gamma-Ray Burst Observatory (CGRO) provided compelling evidence that GRBs are extragalactic and their locations extend up to very large cosmological distances (Meegan, et al. 1992). Such cosmological distances and the prevailing assumption that the emitted radiation in GRBs is isotropic, implied that GRBs are the most energetic and luminous events in the universe since the big bang (Fishman & Meegan 1995). Indeed, the discovery with the Italian-Dutch satellite BeppoSAX that GRBs have a longer-lived X-ray afterglow (Costa et al. 1997) provided accurate enough sky localizations of GRBs, and led to the discovery of their optical afterglow (van Paradijs et al. 1997), their host galaxies and their redshifts, which confirm their enormous luminosities and isotropic equivalent energies, as implied by the observations (Meegan et al. 1992) with the Compton Gamma Ray Observatory (CGRO).

By now, the redshifts of more than 500 GRBs, out of nearly 2000 GRBs, which were located by the Compton, Konus/Wind, BeppoSAX, HETE2, INTEGRAL, Swift, AGILE, Fermi, CALET and AstroSat space based telescopes, have been measured with ground based telescopes and the Hubble space based telescope. The distribution of the isotropic equivalent energy release, $E_{iso}$, of these GRBs show a strong cutoff beyond $\sim 1 \times 10^{54}$ erg (Atteia et al. 2017) with a largest observed value $E_{iso} \approx 3.7 \times 10^{54}$ erg (Atteia et al. 2022), which was measured by Fermi/GBM (Lesage et al. 2022) in GRB 220101A at redshift $z=4.618$ (Fu et al. 2022, Fynbo et al. 2022). So far no GRB model has predicted nor explained the origin of the observed sharp cutoff/maximal value of $E_{iso}$ of GRBs.

In this letter we use two unique properties of cosmic-ray bursts (CRBs) and GRBs, which were predicted by the cannonbal model that unifies CRBs and GRBs (Shaviv & Dar 1995, Dar 1998, Dar & Plaga 1999, Dar & De Rújula 2000,2004,2008, Dado, Dar & De Rújula 2022 and references therein), and have been confirmed by observations, to predict a maximal value $\approx 3.8 \times 10^{54}$ erg of $E_{iso}$ in GRBs. These two properties are the so called Amati correlation in GRBs (Amati et al. 2002, 2006, 2009, 2019) and the knee around 1 TeV in the energy spectrum of cosmic ray electrons (Dado & Dar 2015, De Rújula 2019), which was first indicated by the combined observations of the AMS-02 collaboration (Aguilar et al. 2014) and the H.E.S.S collaboration (Aharonian et al. 2008,2009), and confirmed in more recent observations by the DAMPE collaboration (Ambrosi et al. 2017), and the CALET collaboration (Adriani et al. 2018).

2. THE CANNONBALL MODEL OF GRBS AND CRBS

In the cannonbal (CB) model of GRBs and CRBs bipolar jets of highly relativistic plasmoids (CBs) with an initial Lorentz factor $\gamma(0) \sim 10^3$ are assumed to be launched by matter falling back onto a newly born compact stellar objects (a neutron star, a quark star or a black hole) in stripped envelope supernova explosions of type Ic (SNeIc) and in "failed supernovae" - direct collapse of a massive star to a black hole without a supernova (MacFadyen & Woosley 1999).

The electrons within CBs with a highly relativistic bulk motion produce prompt gamma-ray pulses by inverse Compton scattering (ICS) of photons of the light halo (glory) surrounding the progenitor star. Such a glory is produced by scattered light from pre-collapse ejecta, or from a companion star, or from an accretion disk formed around the compact stellar object. This CB model of GRBs has been extremely successful in predicting the main observed properties of GRBs (e.g. Dado, Dar & De Rújula 2022 and references therein).

CRBs are produced by the highly relativistic jets of CBs by scattering the particles on their path in the interstellar medium (ISM) to cosmic-ray energies (Dar & plaga 1999, Dar& De Rújula 2008). The highest energy that particles of a mass $m_i$ at rest in the ISM can be scattered to by a CB with a Lorentz factor $\gamma(0) \gg 1$ is $\approx 2mc^2[\gamma(0)]^2$. Further increase in their energy can take place in the ISM if they happen to be scattered by other CBs/fast moving matter in the ISM. Such secondary encounters can raise their energy beyond the above limit, and turn it into a CR knee in their energy spectrum, around an energy

$$E_{knee} \approx 2mc^2[\gamma(0)]^2.$$  

The knees in the energy spectrum of cosmic-ray nuclei of charge Ze and mass $\approx A m_p$ seem to satisfy

$$E_{knee}(A) \approx A E_{knee}(p),$$
where \( E_{\text{knee}}(p) \approx 2 \text{ PeV} \). So far measurements of the energy spectrum of cosmic ray nuclei above the atmosphere at PeV energies were not accurate enough to indicate whether the knee energy in their energy spectra is proportional to their rigidity, i.e. \( E_{\text{knee}}(A) \approx Z E_{\text{knee}}(p) \) as widely believed, or to their mass, as expected in the CB model (Dar & De Rújula 2008). By now, this controversy seems to have been settled dramatically in favor of the CB model by the discovery of a knee in the energy spectrum of cosmic-ray electrons (CRe) around

\[
E_{\text{knee}}(e) \approx (m_e/m_p) E_{\text{knee}}(p) \approx 1 \text{ TeV}.
\]

(3)

Evidence for a CRe knee around 1 TeV, was first suggested (Dado & Dar 2015) by combining the observations of CRe above TeV by the H.E.S.S collaboration (Aharonian et al. 2008, 2009) and by the observations of CRe below TeV by the AMS-02 collaboration (Aguilar et al. 2014), as shown in Fig 1. It was later confirmed by the observations of DAMPE (Ambrosi et al. 2018) plus Fermi-LAT (Abdollahi et al. 2017) and by CALET (Adriani et al. 2018) plus AMS-02 (Aguilar al. 2014), as shown in Figures 2 and 3, despite systematic differences in their spectra due to unknown origins.

3. THE MAXIMUM ISOTROPIC ENERGY OF GRBS:

In the CB model, (see e.g., Dado, Dar & De Rújula 2022 for a recent review) fall back material in SN explosions of type Ic (SNeIc) on the newly born compact object results in the ejection of a bipolar jet of highly relativistic plasmoids (CB) of ordinary matter with a large initial bulk motion Lorentz factor \( \gamma(0) \sim O(10^2) \). Inverse Compton scattering (ICS) in the Thomson regime of an isotropic distribution of glory photons in the SNlc rest frame, with a typical peak energy \( \epsilon_p \approx 1 \text{ eV} \), by the electrons in a jet of CBs with a typical initial Lorentz factor \( \gamma(0) \sim O(10^2) \) in the SNlc rest frame at redshift \( z \), yields a GRB photon distribution with a peak energy \( E_p \) in the observer frame that satisfies

\[
(1+\gamma)E_p \approx \gamma(0)\delta(0)\epsilon_p,
\]

(4)

where \( \delta(0) = 1/|\gamma(0)(1-\beta \cos \theta)| \) is the Doppler factor of the GRB viewed from an angle \( \theta \) relative to the CB direction of motion. The isotropic equivalent GRB energy in the SNlc rest frame satisfies

\[
E_{\text{iso}} \propto \gamma(0) [\delta(0)]^3 \epsilon_p.
\]

(5)

ICS of an isotropic photon distribution in the SN rest frame at redshift \( z \), produces a GRB, which is beamed into an angular distribution \( (dn_{GRB}/d\Omega) \approx (n_e/4\pi) \delta^2 \). The mean scattering angle of photons undergoing Compton scattering is \( \pi/2 \), in the CB rest frame or \( \theta = 1/\gamma(0) \), in the observer frame. It yields \( \delta(0) \approx \gamma(0) \), and the Amati correlation

\[
(1+z)E_p \approx [E_{\text{iso}}]^{1/2},
\]

(6)

which follows from Eqs. (4) and (5). This CB model correlation is in excellent agreement with the latest best fit Amati correlation (Amati et al. 2019),

\[
[(1+z)E_p/100 \text{keV}] \approx 115[E_{\text{iso}}/10^{52} \text{erg}]^{0.50 \pm 0.02},
\]

(7)

which was discovered empirically, two decades ago, tested continuously and confirmed repeatedly with new observational data on GRBs (e.g., Amati et al. 2002,2006,2009,2019).

Single scattering of interstellar ionized particles (atomic nuclei of mass \( m_i = m_A \) and electrons of mass \( m_e \), respectively) on their path creates a highly relativistic beam of cosmic ray particles with maximum energies \( E_{\text{max}} \approx 2m_i(\gamma(0))^2 \). In the CB model these maximum energies of ISM particles acquired in a single scattering, are the knee energies in the energy spectra of cosmic ray nuclei and electrons. The first indication of a knee around 1 TeV in the energy spectrum of cosmic ray electrons plus positrons (CRe) was obtained by combining the CRe observations of the H.E.S.S collaboration (Aharonian et al. 2008,2009) and of the AMS collaboration (Aguilar et al. 2014) shown in Figure 1, although the H.E.S.S results were qualified by sizeable systematic uncertainties.

The presence of a CRe knee around 1 TeV (Dado & Dar 2015) in the energy spectrum of Galactic cosmic ray electrons plus positrons (CRe) was recently confirmed in extended CRe observations with DAMPE, the Dark Matter Particle Explorer (Chang et al, 2017) and independently with CALET, the Calorimetric Electron Telescope (Adriani et al. 2018), shown in Figures 2 and 3, respectively.

A CRe knee around \( \approx 1 \text{ TeV} \) implies a maximum initial Lorentz factor \( \gamma(0) \approx 1500 \) of CBs. According to Eq.(4), ICS of glory photons of typical peak energy \( \epsilon_p \approx 1 \text{ eV} \) by inert electrons in CBs with \( \gamma(0) \approx 1500 \) yields

\[
(1+z)E_p \approx 2.25 \text{ MeV}.
\]

(8)

This value of \((1+z)E_p \) and the best fit Amati correlation as given by Eq.(4) yield max \( E_{\text{iso}} \approx 3.80 \times 10^{54} \text{ erg} \). Strictly, this value corresponds to GRBs produced by ICS of glory photons with a peak energy \( \epsilon_p \approx 1 \text{ eV} \) by CBs moving at an angle \( \theta = 1/\gamma(0) \) relative to the line of sight to the GRB. Taking into account the spreads in viewing angle and peak energy of glory photons, this value is actually the value beyond which the observed distribution
Figure 1. A cutoff power-law fit to the combined CRe flux measured near Earth with AMS (full circles: Aguilar et al. 2014) and with H.E.S.S (squares: Aharonian et al. 2008, 2009) The normalization of the H.E.S.S data was adjusted within their estimated systematic error to match the more precise AMS-02 data below TeV (Aguilar et al. 2014).

Figure 2. A broken power-law fit to the CRe spectrum (multiplied by $E^3$) measured by DAMPE (Chang et al. 2017) between 50 GeV - 5 TeV. A CRe knee is indicated by the wide band around 1 TeV.

Figure 3. A broken power-law fit to the CRe spectrum (multiplied by $E^3$) measured with the Calorimetric Electron Telescope (CALET) on the International Space Station, from 11 GeV to 4.8 TeV.

Figure 4. A cutoff power-law fit to the CRe spectrum measured near Earth with AMS (full circles: Aguilar et al. 2014) and with H.E.S.S (squares: Aharonian et al. 2008, 2009) The normalization of the H.E.S.S data was adjusted within their estimated systematic error to match the more precise AMS-02 data below TeV (Aguilar et al. 2014).

4. ONCLUSIONS:

In the CB model, GRBs and CRBs are produced by highly relativistic jets of plasmoids (cannonballs) ejected by fall back material in stripped envelope supernova explosions of massive stars. The knee, which has been discovered recently in the energy spectrum of high energy cosmic ray electrons + positrons, implies a maximum peak energy $(1+z)E_p \approx 2.25$ MeV of GRB photons produced by ICS of glory photons near source. The Amati relation for such a peak photon energy, consistent with that predicted by the CB model, yields a maximum GRB isotropic equivalent energy $E_{iso} \approx 3.8 \times 10^{54}$ erg. This value is consistent with the current highest value, $E_{iso} \approx 3.7 \times 10^{54}$ erg, (Atteia 2022) measured in GRB 220101A (Lesage et al. 2022) at redshift $z = 4.618$ and with an earlier conclusion (Atteia 2017) that the distribution of the isotropic equivalent energy of GRBs has a strong cutoff above $1-3 \times 10^{54}$ erg. This success provides further support to the validity of the unified Cannonball model of cosmic ray bursts and gamma ray bursts and in particular to the conclusion that the knees in the energy spectra of cosmic ray particles is proportional to their...
Figure 4. The best fit Amati correlation (red line) between recalibrated values of $(1+z)E_p$ and $E_{iso}$ of GRBs (black data points), within 1σ and 3σ limits (shaded region) adapted from Amati et al. 2019.

masses (Dar & De Rújula 2008 and references therein) rather than to their rigidities, as widely believed.

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