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The Maximum Isotropic Equivalent Energy of Gamma-Ray Bursts

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Abstract

In the cannonball model of gamma-ray bursts (GRBs), a highly relativistic jet of plasmoids of ordinary stellar matter that is ejected during stellar collapse or shortly after by fallback matter, produces simultaneously a GRB and a cosmic-ray burst by scattering light and charged particles in its path. This association and the observed knee at $\sim$1 TeV in the energy spectrum of Galactic cosmic-ray electrons imply a maximum peak energy $\sim$2.25 MeV in the energy spectrum of GRBs in the 1 keV–10 MeV band. Such a peak energy and the Amati correlation in GRBs imply a maximum isotropic equivalent energy release of $\sim 3.8 \times 10^{54}$ erg in GRBs, in the 1 keV–10 MeV band. Both predictions are in good agreement with up-to-date observations.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739)

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 1967 July 2 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 a 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 GRBs are 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) led to accurate enough sky localizations of GRBs, the discovery of their optical afterglow (van Paradijs et al. 1997), their host galaxies, and their redshifts, which confirmed their enormous gamma-ray luminosities and isotropic equivalent energies, as implied by the CGRO observations (Meegan et al. 1992).

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 Telescope. The peak energy E_p in the energy distribution of their emitted photons in the 1 keV–10 MeV band seems to have a maximum value $(1+z)E_p \approx 2.4$ MeV, and their isotropic equivalent energy release $E_{\rm iso}$ in this band shows a strong cutoff beyond $\sim 1\text{–}3 \times 10^{54}$ erg (Atteia et al. 2017) with a largest observed value $E_{\rm iso} = 3.7 \times 10^{54}$ erg (Atteia 2022), which was measured with Fermi/Gammy-ray Burst Monitor (Lesage et al. 2022) in GRB 220101A at redshift $z = 4.618$ (Fu et al. 2022; Fynbo et al. 2022). The origin of these observed maximum values of $(1+z)E_p$ and $E_{\rm iso}$ in the 1 keV–10 MeV band has not been explained.

In this Letter we use two unique properties of high-energy cosmic rays (CRs) and GRBs, which were predicted by the cannonball model that unifies the production of GRBs and cosmic-ray bursts (CRBs; Dar & Plaga 1999; Dar & De Rújula 2000, 2004, 2008; Dado et al. 2022 and references therein), and have been confirmed by observations to predict the maximum values of $(1+z)E_p$ and $E_{\rm iso}$ in the 1 keV–10 MeV band in GRBs. These two properties are the Amati correlation in GRBs (Amati et al. 2002, 2009, 2019; Amati 2006) 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; Kersberg et al. 2017) and confirmed 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 cannonball (CB) model of GRBs (see, e.g., Shaviv & Dar 1995; Dar & Plaga 1999; Dar & De Rújula 2000, 2004; Dado et al. 2022 for a recent review) 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 object (a neutron star, a quark star, or a black hole) in stripped envelope supernova explosions of Type Ic (SNIc; De Rújula 1987) and in "failed supernovae"—direct collapse of massive stars to black holes without a supernova (MacFadyen & Woosley 1999). GRB photons in the 1 keV–10 MeV band are produced mainly by inverse Compton scattering (ICS) of optical photons in the halo surrounding the progenitor star by CB electrons. ICS of X-ray photons in the Klein–Nishina regime by CB electrons and production of π^0 in hadronic collisions of CBs in the halo can yield higher-energy photons and an $E_{\rm iso}$ that exceeds by far that measured in the 1 keV–10 MeV band, as reported, e.g., by

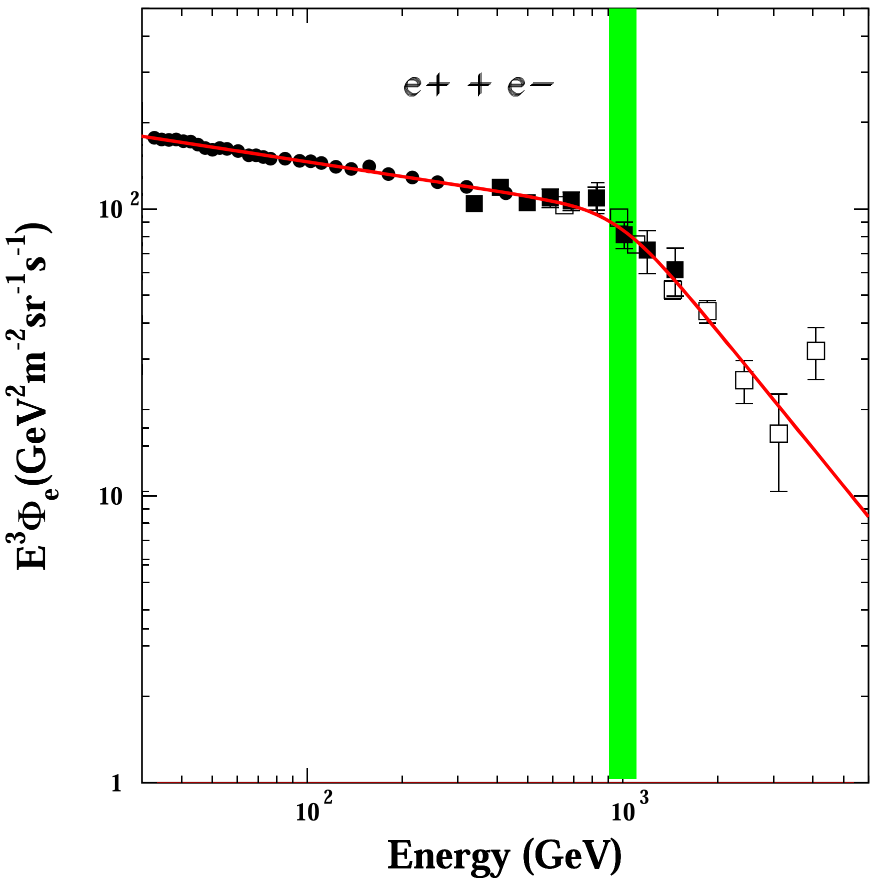

Figure 1. A cutoff power-law fit to the combined CRe flux (multiplied by E^3) measured near Earth with AMS-02 (filled circles: Aguilar et al. 2014) and with H.E.S.S (empty and filled squares: Aharonian et al. 2008, 2009, respectively). The normalization of the H.E.S.S data was adjusted within their estimated systematic error to match the more precise AMS-02 data below TeV.

Amati et al. (2009) for GRB 080916C in the 1 keV–10 GeV band.

CRBs are produced simultaneously with GRBs by highly relativistic jets of plasmoids (CBs) that produce GRBs by scattering particles on their path (Dar & Plaga 1999; Dar & De Rújula 2008). The highest energy, which ionized particles of a mass m_i at rest in the interstellar medium (ISM) can be scattered by a CB with a Lorentz factor $\gamma(0)\gg 1$, is $\approx 2m_i c^2[\gamma(0)]^2$. Further increase in their energy can take place in the ISM if they happen to be scattered by other CBs or by high-energy CR nuclei. Such encounters can raise their energy beyond the above limit, and turn it into a CR knee in their energy spectrum, around an energy

$$E_{\rm knee} \approx 2m_i c^2[\gamma(0)]^2. \tag{1}$$

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

$$E_{\rm knee}(A) \approx A\, E_{\rm knee}(p), \tag{2}$$

where $E_{\rm knee}(p) \approx 2$ PeV. Until recently 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., $E_{\rm knee}(A)\approx Z\, E_{\rm knee}(p)$ 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 in favor of the CB model by the discovery of the knee in the energy spectrum of cosmic-ray electrons (CREs) around

$$E_{\rm knee}(e) \approx (m_e/m_p) E_{\rm knee}(p) \approx 1\ \mathrm{TeV}. \tag{3}$$

3. The Maximum Isotropic Energy of GRBs

In the CB model, ICS in the Thomson regime of an isotropic distribution of photons in a halo around a nascent SNIc at redshift z with a typical peak photon energy $\epsilon_p \approx 1$ eV, by the electrons in a CB with an initial Lorentz factor $\gamma(0)\sim 10^3$, yields a GRB pulse with a peak photon energy E_p in the observer frame, which satisfies

$$(1+z)E_p \approx \gamma(0)\delta(0)\epsilon_p, \tag{4}$$

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

$$E_{\rm iso} \propto \gamma(0)[\delta(0)]^3\ \epsilon_p. \tag{5}$$

ICS of an isotropic photon distribution in the SN rest frame at redshift z produces a GRB, which is beamed into an angular distribution $(dn_\gamma/d\Omega) \approx (n_\gamma/4\pi)\delta^2$. 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

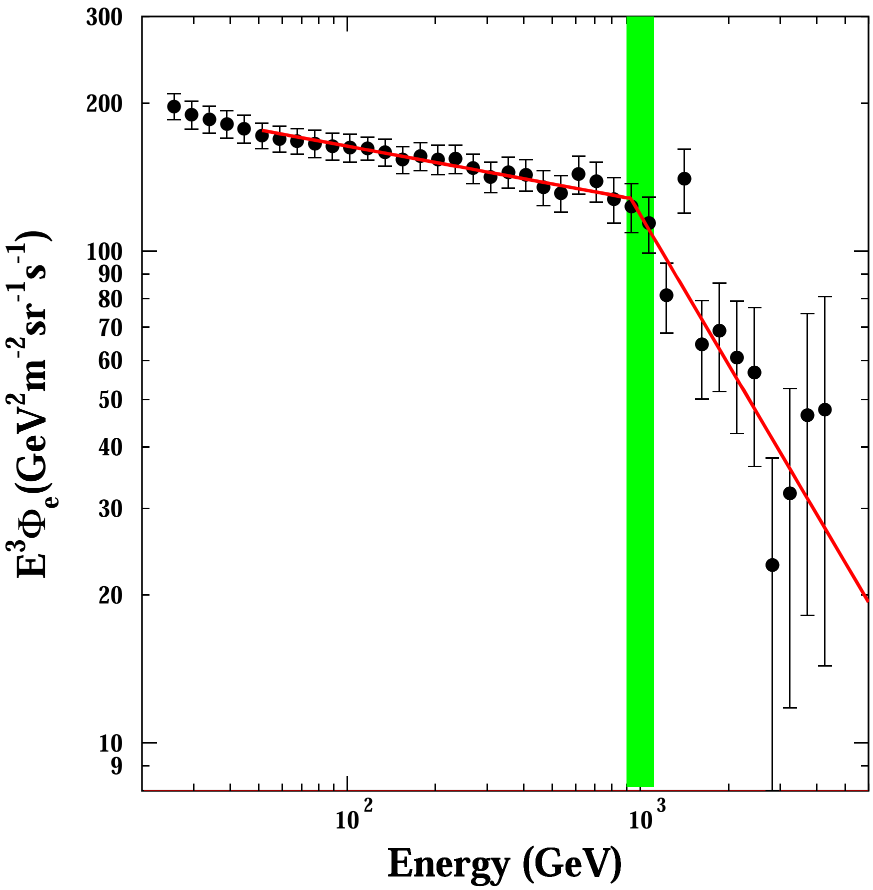

Figure 2. A broken power-law fit to the CRE spectrum (multiplied by E^3) measured by DAMPE (Chang et al. 2017) between 50 GeV and 5 TeV. A CRE knee is indicated by the wide band around 1 TeV.

$\delta(0) \approx \gamma(0)$, and the Amati correlation for near-axis GRBs,

$$(1 + z)E_p \propto [E_{\rm iso}]^{1/2}, \tag{6}$$

which follows from Equations (4) and (5). This CB model correlation for near-axis GRBs is in excellent agreement with the latest best-fit Amati correlation (Amati et al. 2019),

$$[(1 + z)E_p/100\,{\rm keV}) \approx 115[E_{\rm iso}/10^{52}\,{\rm erg}]^{0.50\pm0.02}, \tag{7}$$

for near-axis GRBs ($\theta \approx 1/\gamma(0)$), which was discovered empirically, two decades ago, tested continuously, and confirmed repeatedly with new observational data on GRBs (e.g., Amati et al. 2002, 2009, 2019; Amati 2006).

Note that in the CB model, GRBs that are viewed from far off-axis, i.e., $\theta \gg 1/\gamma(0)$, have a relatively low luminosity and low $E_{\rm iso}$ compared to those of ordinary, near-axis GRBs. Such far off-axis GRBs satisfy (Dar & De Rújula 2000; Dado et al. 2022, and references therein)

$$(1 + z)E_p \propto [E_{\rm iso}]^{1/3}. \tag{8}$$

Consequently, the entire population of GRBs, which is a mixture of near-axis and far off-axis GRBs, is expected to satisfy the Amati correlation with a mean power index $1/2(1/2 + 1/3) \approx 0.42$, in agreement with that reported for the entire population of GRBs (near- and far off-axis) observed so far with secured redshift, E_p, and $E_{\rm iso}$ values (e.g., Tsvetkova et al. 2021; Rossi et al. 2022).

On their path, scattering of interstellar ionized particles (atomic nuclei of mass $m_i = m_A$ and electrons of mass m_e) by CBs produces a highly relativistic beam of cosmic-ray particles with maximum energies $E_{\rm max} \approx 2m_i[\gamma(0)]^2$. In the CB model these maximum energies are the knee energies in the energy spectra of cosmic-ray nuclei and electrons (Dar & De Rújula 2008). The first indication of such a knee around 1 TeV in the energy spectrum of cosmic-ray electrons plus positrons (CREs) 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 sizable 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 confirmed in more recent extended CRE observations with H.E.S.S. (Kersberg et al. 2017), and with the Dark Matter Particle Explorer (DAMPE; Chang et al. 2017) and the Calorimetric Electron Telescope (CALET; Adriani et al. 2018), shown in Figures 2 and 3, respectively.

A CRE knee around $\approx$1 TeV implies a maximum initial Lorentz factor $\gamma(0) \approx 1500$ of CBs. According to Equation (4), ICS of glory photons of typical peak energy $\epsilon_p \approx 1$ eV by inert electrons in CBs with $\gamma(0) \approx 1500$ yields a strong cutoff in $(1 + z)E_p$ around

$$(1 + z)E_p \approx [\gamma(0)]^2\ {\rm eV} \approx 2.25\ {\rm MeV}. \tag{9}$$

This value of $(1 + z)E_p$ and the best-fit Amati correlation as given by Equation (7) for near-axis GRBs yield a sharp max

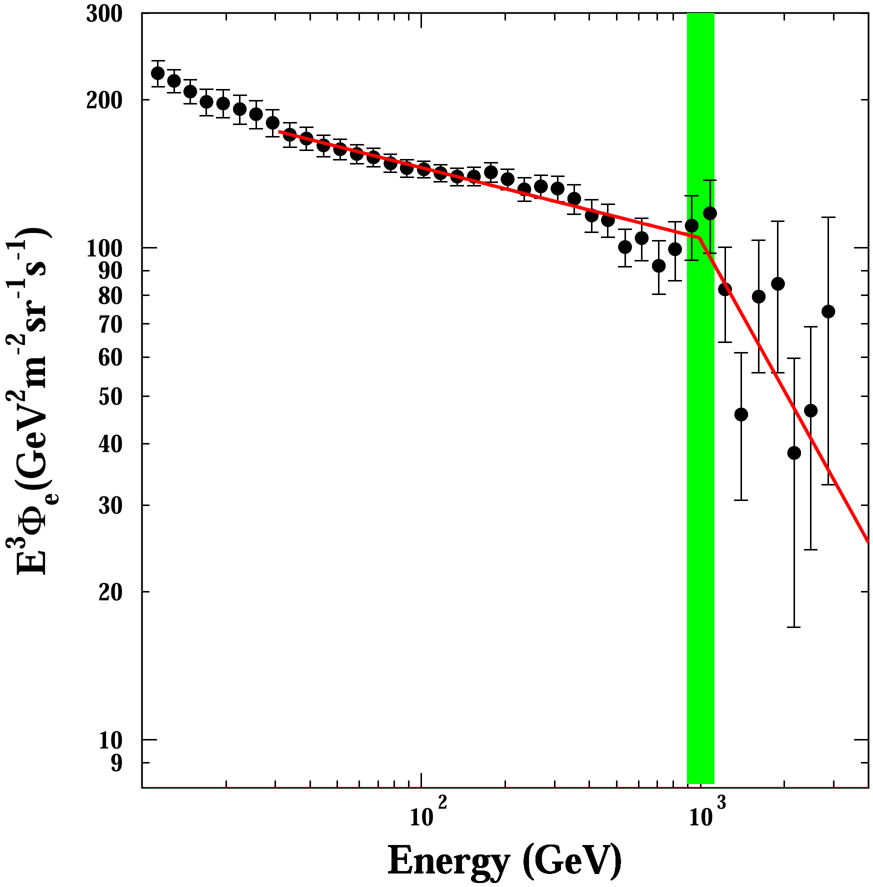

Figure 3. A broken power-law fit to the CRE spectrum (multiplied by E^3) measured with the Calorimetric Electron Telescope (CALET) on the International Space Station, from 11 GeV to 4.8 TeV.

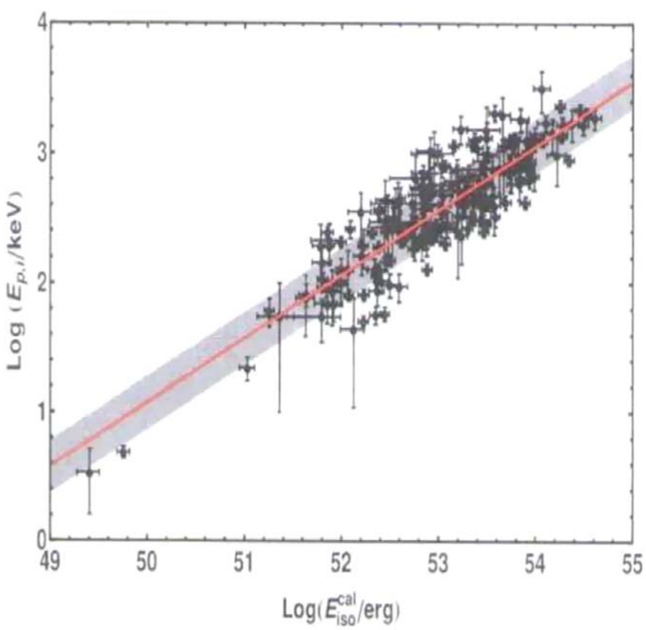

Figure 4. The best-fit Amati correlation (red line) between recalibrated values of $(1 + z)E_p$ and E_{iso} of GRBs (black data points), within 1σ and 3σ limits (shaded region) adapted from Amati et al. (2019).

$E_{\mathrm{iso}} \approx 3.80 \times 10^{54}$ erg. Strictly, this value corresponds to GRBs produced by ICS of glory photons with a peak energy $\approx$1 eV by CBs moving at an angle $\theta \approx 1/\gamma(0)$ relative to the line of sight to the CB location. 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 of E_{iso} of GRBs is predicted to have a strong cutoff. This strong cutoff is evident, e.g., in Figure 4 adapted from Amati et al. (2019), and in up-to-date compilations of measured E_{iso} values of GRBs with known redshift (e.g., Figure 8 in Rossi et al. 2022).

4. Conclusions

In the CB model, GRBs and CRBs are produced simultaneously by highly relativistic jets of plasmoids (cannonballs) ejected by fallback material in stripped envelope supernova explosions of massive stars. The observed knee, in the energy spectrum of high-energy cosmic-ray electrons and positrons, implies a maximum peak energy $(1 + z)E_p \approx 2.25$ MeV of GRB photons produced by ICS of glory photons near the source. The Amati relation for such a peak photon energy yields a maximum GRB isotropic equivalent energy $E_{\mathrm{iso}} \approx 3.8 \times 10^{54}$ erg in the 1 keV–10 MeV band. This value is consistent with the current highest value, $E_{\mathrm{iso}} \approx 3.7 \times 10^{54}$ erg (Atteia 2022), measured in GRB 220101A (Lesage et al. 2022) at redshift $z = 4.618$ and with an earlier conclusion (Atteia et al. 2017) that the distribution of the isotropic equivalent energy of GRBs has a strong cutoff above 1–3 $\times$ 10^{54} erg. It provides further support to the validity of the cannonball model that unifies cosmic-ray and gamma-ray bursts and, in particular, the conclusion that the knee energy in the spectra of cosmic-ray particles is proportional to their mass (Dar & De Rújula 2008 and references therein) rather than to their rigidity as widely believed.

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