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The 111-Years-Old Cosmic Ray Puzzle Has Been Solved?

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Abstract

We show that recently multi-messenger astronomy has provided compelling evidence that the bulk of high energy cosmic rays (CRs) are produced by highly relativistic narrow jets of plasmoids launched in core collapse of stripped-envelope massive stars to neutron stars and stellar mass black holes. Such events produce also a visible GRB if the jet happens to point in our direction. This has been long advocated by the cannon ball (CB) model of high energy CRs and GRBs, but the evidence has been provided only recently by what were widely believed to be unrelated discoveries. They include the very recent discovery of a knee around TeV in the energy spectrum of high energy CR electrons, the peak photon energy in the “brightest of all time” GRB221009A, and the failure of IceCube to detect high energy neutrinos from GRBs, including GRB221009A. They were all predicted by the cannonball (CB) model of high energy CRs and GRBs long before they were discovered in observations, despite a negligible probability to occur by chance.

Keywords

Cosmic Rays, Gamma Ray Bursts, Neutrino Bursts

1. Introduction

Cosmic rays (CRs) are mostly high energy, stable, charged particles (protons, nuclei and electrons) which reside in the interstellar and intergalactic space. They were discovered in 1912 by Victor Hess [1]. Their scattering by interstellar and intergalactic magnetic fields so far has prevented identification of their main sources, and the origin of their high energies is still debated. In 1949 Fermi suggested [2] that their high energies are acquired by being reflected from interstellar “magnetic mirrors”—magnetized clouds, which move slowly in random directions in the interstellar medium. However, CR particles may loose energy by synchrotron radiation faster than they gain by repeated magnetic reflections. Consequently, the original Fermi acceleration mechanism has been replaced by the so called Fermi shock acceleration [3]-[9]. In this model charged particles are assumed to gain energy by being scattered repeatedly between the upstream and downstream regions of strong shocks produced, e.g., by supernova shells expanding into the interstellar medium. This shock acceleration mechanism is widely believed to be the main origin of galactic and extragalactic cosmic rays.

An alternative model of CR acceleration [10]-[15], later called the cannonball (CB) model, unified the production of cosmic ray bursts (CRBs) and gamma ray bursts (GRBs). In this cannonball model, highly relativistic jets of plasmoids (CBs) of ordinary stellar matter are launched by fall back matter on a newly born neutron star or a stellar black hole in core collapse explosion of stripped envelope massive stars. GRBs are produced by inverse Compton scattering (ICS) of light photons on the path of the jet by the electrons in the plasmoids [16] [17], while magnetic reflection of the charged particles by the plasmoids produces the high energy cosmic rays [10]-[15]. In the CB model, the CR knee is the maximum energy that CR particles of a given type (electrons, protons or nuclei) acquire in a single magnetic reflection. These knee energies depend only on the largest Lorentz factor of the plasmoids in such jets and on the mass of the CR particles. In the CB model, CRs with energy above their knee are CRs which were reflected backward from slower CBs or supernova shells which were ejected earlier. This interpretation is different from that adopted in the Fermi/shock acceleration models, where the CR knee depends on their rigidity $R = pc/Z$, namely on the momentum of the CR particle multiplied by the speed of light per unit charge.

2. The Knee Energy of Cosmic Rays

The energy spectrum of high energy CR nuclei from well below to well above the CR knee is shown in **Figure 1** adopted from [18].

Until recently the measured knee energies of individual cosmic ray nuclei were not accurate enough to conclude whether they depend on their masses, as expected in the CB model [13], or on their rigidities as expected in the Fermi/shock acceleration models. However, while the rigidities of high energy electrons and protons are practically equal, their masses are very different; $m_p/m_e \approx 1836$. In the CB model, that implies knee energies of high energy CR electrons which satisfy [13] [14] [15],

$$E_{knee}(e) \approx (m_e/m_p) E_{knee}(p) \approx 1\,\text{TeV}. \tag{1}$$

Fortunately, during the past decade, precise enough measurements of the energy spectrum of CR electrons were extended into the TeV range, in particular by the H.E.S.S [19] [20], AMS [21], Fermi-LAT [22], DAMPE [23] and CALET [24] collaborations. As shown in **Figure 2**, they have confirmed the existence of a knee around ~1 TeV in the energy spectrum of high energy cosmic ray electrons, which was predicted by the CB model [13] [14] [15] using the observed knee around 2 PeV [18] in the energy spectrum of cosmic ray protons.

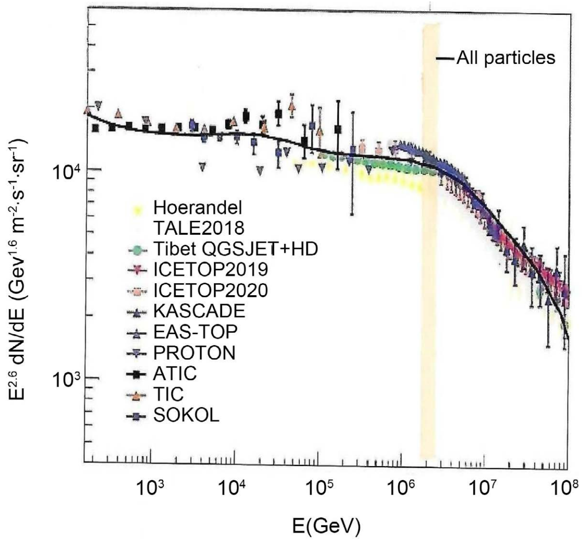

Figure 1. The energy spectrum of cosmic ray nuclei around the cosmic ray knee reported in [18]. The knee energy of cosmic ray protons is indicated by the wide band around 2 PeV.

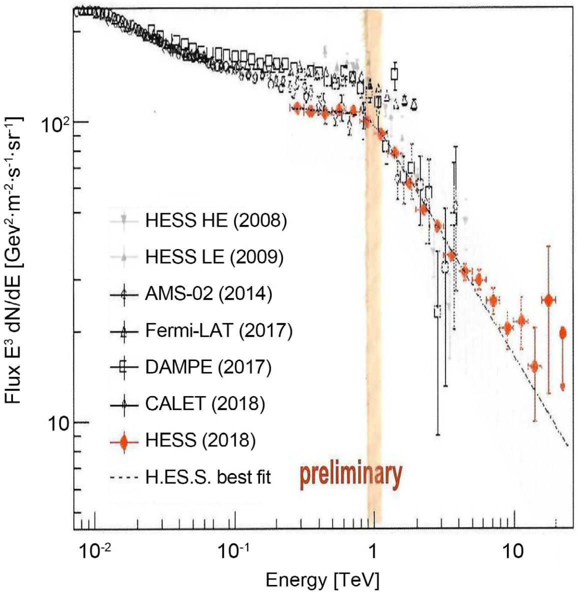

Figure 2. The high energy spectrum of cosmic ray electrons compiled in [19]. The electron knee energy predicted by the CB model is indicated by the vertical band around 1 TeV.

Moreover, the observed knees in the energy spectra of cosmic ray nuclei [18] and electrons [19]-[24] imply that the largest Lorentz factor of CBs fired ($t = 0$) by the main source of high energy CRs, is roughly,

$$\gamma_{max}(0) \approx \sqrt{E_{knee}(CR)/2m_{CR}c^2} \approx 1000. \tag{2}$$

In the CB model, this value of $\gamma_{max}(0)$ of CBs at launch is common to both the electrons and protons nearly at rest in the CBs. It allows the following critical tests of the common origin of CRs and GRBs.

3. Evidence from GRB 221009A

In the CB model, the peak energy E_p of the time integrated distribution of the prompt emission photons of a GRB, which is produced by inverse Compton scattering (ICS) of optical photons ($\varepsilon \approx 1.65\,\text{eV}$, *i.e.*, $\nu = 4\times10^{14}\,\text{Hz}$) by CB electrons having $\gamma_{max} \approx 1000$, is given by

$$max\left[(1+z)E_p\right] \approx 2(\gamma_{max})^2\,\varepsilon \approx 3.3\,\text{MeV}. \tag{3}$$

Indeed, this value is consistent with the measured $(1+z)E_p = 3503 \pm 133$ keV, [25] of the "brightest of all time" GRB 221009A at redshift $z = 0.151$.

Moreover, the time averaged peak photon energy $E_p \approx 2.912$ MeV and the isotropic equivalent energy release, $E_{iso} \approx (1.2 \pm 0.1)\times10^{55}$ erg measured in GRB 221009A [25] are the record high values measured so far in a GRB. Such high values are estimated to be observed once in 10,000 years. They were shown [25] to be consistent with the best fit Amati correlation [26],

$$(1+z)E_p \propto \left[E_{iso}\right]^{0.42}, \tag{4}$$

in a sample of 315 Konus-Wind GRBs, which is shown in **Figure 3**.

In the CB model [17 for a review], far off axis GRBs, *i.e.*, those which are viewed from angles that satisfy, $\theta^2\gamma^2 \gg 1$, have relatively low $(1+z)E_p$ and E_{iso} values which satisfy,

$$(1+z)E_p \propto \left[E_{iso}\right]^{1/3}. \tag{5}$$

Near axis GRBs, *i.e.*, those with viewing angles that satisfy, $\theta^2\gamma^2 \le 1$, have relatively large $(1+z)E_p$ and E_{iso} values and satisfy the correlation [26],

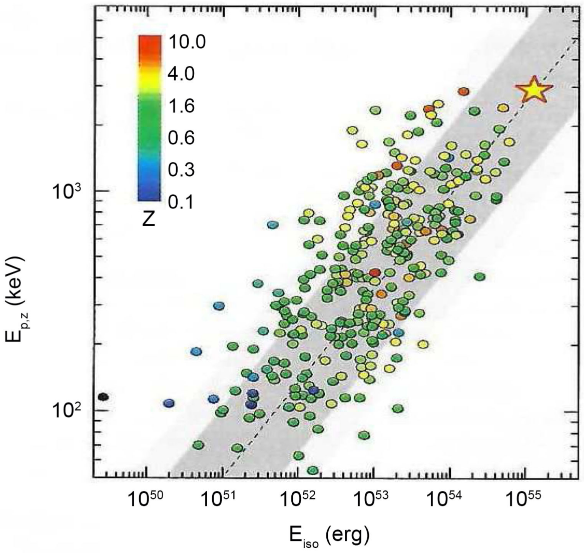

Figure 3. The best fit Amati correlation reported in [25] for 315 long GRBs with known redshift observed by Konus-Wind. GRBs are represented by circles; the color of each data point represents the GRB redshift. The error bars are not shown for reasons of clarity. GRB221009A is indicated by a red star. The best fit Amati relation is plotted as a dashed line.

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

Consequently, a mixed population of near axis and far off axis GRBs is expected to satisfy the Amati correlation [26] with an average power-law index $(1/2+1/3)/2 \approx 0.42$. Indeed it is that reported in [25], and is shown in **Figure 3**. Moreover, a sum of two power laws corresponding to low and high values of $(1+z)E_p$,

$$(1+z)E_p = aE_{iso}^{1/3} + bE_{iso}^{1/2} \tag{7}$$

also describes well the mixed population of far off axis GRBs and near axis GRBs.

4. The Missing GRB Neutrinos

The jet of highly relativistic CBs, which produces a GRB, propagates through the interstellar medium and/or stellar shells ejected earlier. Its nucleons produce a narrow conical beam of short lived high energy pions and kaons along the axis of the much wider GRB cone [13]. Their decay produces a narrow conical beam of high energy gamma rays, electron and muon neutrinos. Since the transverse momentum of their parent π and K mesons is of the order of their masses [27], their produced high energy neutrinos and gamma rays (in the source rest frame) are mainly within a cone of an opening angle $\approx m_\pi/\gamma m_p$. The high energy gamma rays from GRBs are attenuated by pair production on background photons [28], while the high energy neutrinos are not attenuated. Both are emitted into a cone much narrower than that of the MeV gamma rays from a GRB. But, the small cross section of neutrinos and the CB model estimate [13] of the flux of GRB neutrinos imply that the chances to detect on Earth the narrow burst of high energy (TeV) neutrinos from a GRB are rather small. That is consistent with the reported failure by the IceCube collaboration [29] to detect high energy neutrinos from GRBs, including GRB 221009A.

5. Conclusion

Multi-messenger astronomy has recently provided compelling evidence in support of the CB model solution of the 111-years-old cosmic ray puzzle. Namely, the bulk of high energy cosmic rays (CRs) are produced by the highly relativistic narrow jets of plasmoids of ordinary stellar matter launched in core collapse of stripped-envelope massive stars to neutron stars and stellar mass black holes. Such events produce also visible GRBs only when the jet happens to point near our direction, but very rarely a detectable narrower neutrino burst. The maximal peak energy of GRBs, as measured in “the brightest of all time” GRB 221009A [30] correctly predicts the observed knee energies of CR protons, nuclei and electrons. The chances to detect the expected very narrow burst of neutrinos from a GRB by detectors such as IceCube are very small, even for record bright events like GRB 221009A. Despite the above, a complete understanding of how such highly relativistic jets of plasmoids are formed and why the maximum bulk motion Lorentz factor of their plasmoids is ≈1000 is still lacking.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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