

# The vicissitudes of “cannonballs”: a response to criticisms by A.M. Hillas and a brief review of our claims

Arnon Dar

*Department of Physics and Space Research Institute, Technion, Haifa 32000, Israel*

A. De Rújula

*Theory Unit, CERN, 1211 Geneva 23, Switzerland; Physics Department, Boston University, USA*

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A.M. Hillas, in a review of the origins of cosmic rays, has recently criticized the “cannonball” (CB) model of cosmic rays and gamma-ray bursts. We respond to this critique and take the occasion to discuss the crucial question of particle acceleration in the CB model and in the generally accepted models. We also summarize our claims concerning the CB model.

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## I. MOTIVATION

The ‘cannonball’ (CB) model is based on the hypothesis that a good fraction of core-collapse SNe biaxially emit a few plasmoids of ordinary matter, initially expanding (in their rest system) at the speed of sound in a relativistic plasma. The CBs have a typical initial Lorentz factor of  $\mathcal{O}(10^3)$  and a baryon number of  $\mathcal{O}(10^{50})$ , roughly corresponding to half the mass of Mercury. We contend that this model provides a good, simple, few-parameter description of the properties of cosmic rays (CRs), long-duration gamma-ray bursts (GRBs), X-ray flashes, the gamma background radiation, the natal kicks of neutron stars, the magnetic fields of galaxy clusters, and the ‘cooling flows’ of rich clusters.

The CB model is no doubt a considerable simplification, and may of course be false. One way to express our claims —undeniable, in our opinion— is the following. The model is an excellent mnemotechnic pedagogical tool: practically every single property of the mentioned phenomena can be derived, in the proverbial extent of the back of an envelope, from the stated hypothesis, a few auxiliary observations (e.g. the density of the interstellar medium) and elementary physics considerations.

In an a-posteriori addition to a contribution to a conference [1], A.M. Hillas has made criticisms of the CB model. We are very grateful to receive an open critique since, up to now, written comments on this model were confined to the asymmetric environment of anonymous referee’s reports.

In criticizing the CB model, Hillas gives a brief outline of it. We will quote large portions of Hillas’ article, since his outsider’s explanations are also useful here, and are concordant in style with his critical comments. Quotes from Hillas will be in italics, e.g. *The authors have gone on to estimate (most fully in Dar and de Rújula [2]) that these objects [CBs] would also naturally account for the generation of virtually all cosmic rays as a consequence of their motion through the interstellar gas. However, I can give no credence to this model.*

## II. ON THE EXPANSION OF CANNONBALLS

*The vital properties of the cannonball are its Lorentz factor,  $\Gamma$ , which determines the energy of the particles it emits, and its transverse radius,  $R$ , which determines the rate at which particles are swept up and the CB slows down. A quite false effect is employed in calculating that the expansion of  $R$  is quickly slowed down... The swept-up particles, which have a very high individual energy  $\Gamma m_p c^2$  in the CB reference frame, and which are supposed to diffuse out of the CB, are said to exert an inward pressure, opposing lateral expansion, supposedly because of momentum reaction when they leave, whereas the opposite is true: near the edges, where the net particle flow is outwards, a net outward force (pressure gradient) would be exerted by the diffusing particles on the CB material.*

Consider the analogous problem of photons diffusing outwards in the Sun and finally escaping freely from its “surface”: the photosphere. Their diffusion gradient indeed corresponds to a volume-distributed upwards force. But the escaping photons do exert an inwards force per unit surface on the photosphere. If Hillas were saying the contrary, he would not be contradicting us, but Newton. Our arguments concerning expansion apply to the whole CB or, in the analogy, to the inwards pressure on the Sun’s photosphere.

We explicitly admit in our papers to not having solved the problem of the evolution of a CB from first principles. But we recall how the relativistic plasmoids ejected by quasars appear not to expand laterally as they travel for hundreds of kiloparsecs, before they finally stop and blow up. This is an observation, recognized as a mysterious fact, that we try to explain. Hillas ignores this fact, as well as the success of our entirely analogous choice of CB-radius evolution in the description of the afterglows of GRBs.

## III. ON THE RECAPTURE OF COSMIC RAYS

*The authors suppose that particles can simply leave the*

CB's surface, without Fermi "bouncing", whereas Achterberg et al. [3] show that particles entering a plasma advancing with ultrarelativistic speed, and scattered back out of it, cannot escape: even a small external magnetic field retards them sufficiently that they are recaptured, and a Fermi acceleration process is set up that dominates the spectrum. (If  $B$  were as small as the normal Galactic field  $\sim 2\mu\text{G}$  they would still be recaptured within the CB radius until their rigidity exceeded  $\sim 10^{17}$  V.)

The calculations that Hillas quotes are not relevant. One reason is that a CB is preceded by the collimated flux of CRs it has previously produced, and this flux is largely sufficient to wipe out the pre-existing magnetic field. An analogous phenomenon is the effect of the Sun's coronal mass ejections on interplanetary magnetic fields.

A CB of Lorentz factor  $\Gamma$  intercepts the particles at rest in the ISM (mainly protons, of number density  $n_p$ ) and, via the dominant 'elastic' process, re-emits them in a forward cone of characteristic angular width  $\theta = 1/\Gamma$ , with a typical Lorentz factor  $\gamma \sim \Gamma^2$ . Let the CB and CR velocities, in  $c = 1$  units, be  $\beta_{\text{CB}} \approx 1 - 1/(2\Gamma^2)$ , and  $\beta_{\text{CR}} \approx 1 - 1/(2\gamma^2)$ . The number of ISM particles intercepted by the CB in an element of travel distance,  $dx = \beta_{\text{CB}} c dt$ , is  $\pi R^2 n_p dx$ . They travel forwards in a layer of foreshortened depth  $d\bar{x} = dx(\beta_{\text{CR}}/\beta_{\text{CB}} - 1) \approx dx/(2\Gamma^2)$ . At a later time  $t$ , let  $d = \beta_{\text{CR}} ct$  be the distance travelled by the CRs of our elemental volume, bigger than the distance  $\beta_{\text{CB}} ct$  travelled by the CB. The energy density of CRs inside the leading conical shell of radius  $\theta d$  and depth  $d\bar{x}$  is:

$$\epsilon_{\text{CR}} = \frac{2 R^2 n_p \Gamma^6 m_p c^2}{d^2} \sim 2 \times 10^7 \frac{\text{eV}}{\text{cm}^3} \times \left[ \frac{\Gamma}{10^3} \right]^6 \left[ \frac{R}{10^{14} \text{cm}} \right]^2 \frac{n_p}{10^{-3} \text{cm}^{-3}} \left[ \frac{10 \text{kpc}}{d} \right]^2 \quad (1)$$

This number is very large, with respect to the energy density  $\epsilon_B \sim 0.16 \text{ eV/cm}^3$  of a  $B = 2\mu\text{G}$  field. At the beginning of a CB's trajectory,  $d$  is small and the CR energy density in front of it is enormous. Even a tiny fraction of CRs evading recapture would suffice to erase any previous magnetic field so that the process underlying Eq. (1) can start. It could be argued that we should have adiabatically 'compressed' the ambient magnetic field by the ratio  $d\bar{x}/dx$ . This would not change the conclusion. Moreover, it is no doubt incorrect. The ISM into which the CRs are emitted was previously totally ionized by the GRB's  $\gamma$  rays, becoming a highly conducting plasma. In such a medium the compressed magnetic fields pointing in various directions would efficiently 'reconnect' and 'annihilate'. The CB-generated CRs travel in a domain wherein there is no magnetic field, long enough for the (decelerating) CB not to catch up with them.

#### IV. ACCELERATION WITHIN A CB

*The CB authors do wish to use Fermi acceleration to get particles to  $10^{21}$  V, however, but seem to misinterpret*

*the reports of Frederiksen et al. [4, 5], as showing that relevant acceleration of ions will occur entirely behind the shock, so they considered motion entirely there.*

The expression *behind the shock* may not be the right one, for the quoted papers contain 'collisionless shocks' as part of their titles, but their results do not show anything like the development of a shock.

*Frederiksen et al. did note, though, that the magnetic field in the external medium was required for significant energy gain by ions.*

This is what the quoted authors actually say: "Frederiksen et al. [5] reported evidence for particle acceleration with electron  $\gamma$ 's up to  $\sim 100$ , in experiments with an external magnetic field present in the upstream plasma. This is indeed a more promising scenario for particle acceleration experiments, although in the experiments by Nishikawa et al. [6] results with an external magnetic field were similar to those without." The cited 'experiments' do not seem to us to refer to ions in this context of 'external' magnetic fields. Also, the results are not decisive. Acceleration playing a crucial role in theories of CRs and GRBs, we discuss it some more.

#### V. MORE ON ACCELERATION IN THE MERGERS OF PLASMAS

The required efficiency of the acceleration mechanisms invoked in the CB model is orders of magnitude smaller than that required in the SN remnant (SNR) model of CR production. To generate the CR fluxes up to the 'knees' (predicted to occur at  $E(A) = 2 A m_p c^2 \Gamma_0^2$ , with  $\Gamma_0 \sim 10^3$ ) **no** CR 'acceleration' mechanism is invoked in the CB model. These CRs originate in a single 'elastic collision' of a CB and an ISM particle at rest. In contrast, the CRs of SNR models must laboriously be accelerated by multiple passages through a non-relativistic shock. In the CB model only the CRs above the knee are accelerated in the relativistic merger of two plasmas. This fraction of the observed CR flux is  $10^{-12}$  to  $10^{-13}$  of the total. Numerical experiments may not be able to 'measure' such a small fraction.

Similar differences in the required acceleration efficiency appear in the comparison of the CB model with the standard 'fireball' model of GRBs and their afterglows. The  $\gamma$ -ray spectrum of a GRB is a broken power law changing fast from  $E^{-\alpha}$  to  $E^{-\beta}$  at a 'peak' energy  $E_p$  (typical values, predicted by the CB model, and observed, are:  $\alpha \sim 1$ ,  $\beta \sim 2.1$ ,  $(1+z)E_p \sim 250 \text{ keV}$ ). The largely dominant number of  $\gamma$  rays below  $E_p$  is generated in the elastic Compton scattering of ambient photons by (non-accelerated) electrons comoving with the CB, in very close analogy with the generation of CRs below the knee. At optical frequencies, the afterglow of a GRB is also a broken power law whose indices and 'bend' frequency are correctly predicted by the CB model. Only the very small fraction of the afterglow light lying above the bend frequency is emitted by accelerated electrons.

The broken power-law spectra of CRs, GRBs and their afterglows, as we have seen, have a common explanation, and do not require, except above their ‘knees/peaks/bends’ a population of accelerated ions or electrons. Naturally, the CBs themselves must have been accelerated somehow. The SNR models also require a ‘first acceleration’: that of the SN shell; the fireball models require the acceleration of their thin conical shells of relativistic  $e^+e^-$  pairs. None of these pre-accelerations is convincingly understood on fundamental grounds.

## VI. CONCLUSIONS

We have presented some of the reasons why the critique of the CB model by Hillas does not convince us. More significant than the criticisms of Hillas and many a referee is the general immunity to the evidence in favour of the model. Some examples of this evidence are:

- A few parameters (initial Lorentz factor, typical mass and radio self-absorption frequency of a CB) and their distributions are extracted from the model’s accurate description of GRB afterglows (AGs). **GRB afterglows are understood** [7, 8].
- The AG description was used to conclude that **long-duration GRBs are made by supernovae** [7] and to predict the date in which GRB-associated SNe would be detectable [9]. One example is SN2003dh, associated with GRB 030329, which changed the GRB community’s views from considering the GRB/SN association a marginal item (see, e.g. [10]) to a crucial one (see e.g. [11]). The non-relativistic ejecta of a SN close to its GRB axis are faster than average: these conventional SNe **appear to be ‘hypernovae’** [11], but they are not.
- At small redshifts the CBs of a GRB ought to be directly observable as superluminal sources of their radio AG [12]. One example is the two-pulse (two-CB) GRB 030329 [9, 13], whose double-source radio AG was indeed observed [14, 15]: **GRB cannonballs have been seen**.
- Given the information extracted from their AGs, all the properties of the single  $\gamma$ -ray pulses of GRBs are predicted in the CB model, in agreement with observations [16]. **Long GRBs are understood**.
- The X-ray AGs of GRBs are predicted to have a specific complicated structure [7]. This has recently been corroborated in impressive detail by SWIFT [17, 18]. **The early evolution of CBs is understood**.

- The geometrical and radiation-beaming properties of a CB are trivial: those of an effectively point-like relativistic source. Consequently, many observable properties of a GRB (e.g. peak energy and isotropic energy and luminosity) are related to one another by predicted power laws [16, 19], in agreement with observations [16, 20]. GRB radiation is extremely collimated: **a good fraction of core-collapse SNe emit GRBs**.
- **X-ray flashes are nothing but GRBs observed at larger angles**, as supported by their properties [16, 21], including their origin in SN explosions [21, 22].
- The spectral shapes and relative abundances of CRs up to their knees are predicted, and in agreement with observations [2]. The predictions are parameter-free and do not invoke any iterative acceleration mechanism. **CRs are understood up to the knees** and their understanding is trivial.
- The tiny fraction of CR flux above the knees requires, in the CB model, an iterative acceleration akin to that required at all energies in the standard models of CRs and GRBs. With only one parameter for what this fraction is, the observed fluxes of CRs above the knees (and above the analogous energies in GRBs and their AGs) are understood. **The entire spectra of CRs and GRBs are explained** with a single source: cannonballs.
- The CB model also offers straightforward explanations of the natal kicks of neutron stars [23], the properties of the gamma background radiation [24, 25], of cooling flow clusters [26], and of the intensity of magnetic fields in the intergalactic space, including that in galaxy clusters [27]. **The CB model is a proposed simple description of all high-energy astrophysical phenomena generated by relativistic jets**.

Faced with these items, we conclude that there is a choice between Okcam’s razor and the opposite view: *For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation* (Tommy Gold).

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