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# The gravitational wave and short gamma-ray burst GW170817/SHB170817A

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**Summary.** — This event, so far unique, beautifully confirmed the standard views on the gravitational waves produced by a merger of two neutron stars, but its electromagnetic multi-wavelenth observations disagreed with the numerous initial versions of the "standard fireball model(s)" of gamma ray bursts. Contrariwise, they provided strong evidence in favour of the "cannonball" model. Most uncontroversially, a cannonball was observed at radio wavelengths, with an overwhelming statistical significance ($> 17\,\sigma$), and travelling in the plane of the sky, as expected, at an average apparent superluminal velocity $V_{app} \sim 4\,c$.

## 1. – Introduction

The GW170817 event was the first binary neutron-star merger detected with Ligo-Virgo [1] in gravitational waves (GWs). It was followed by SHB170817A([1]), 1.74±0.05 s after the end of the GW's detection. The SHB's afterglow across the electromagnetic spectrum was used to localize its source [2] to the galaxy NGC 4993, at a cosmologically very modest redshift, $z = 0.009783$. The GW170817/SHB170817A association was the first indisputable confirmation that pairs of neutron stars merging due to GW emission produce GRBs, thereafter converting this suggestion [3, 4] into a general consensus.

Not so well known is the fact that two days before the discovery date, a paper appeared on arXiv [5], not only reiterating the neutron star merger hypothesis, but predicting that a SHB found in combination with a GW would be seen far off axis. The prediction was based on the much greater red-shift reach of GRB or SHB observations relative to the GW ones and the fact that the $\gamma$ rays are extremely collimated: within the volume reach of GW observations, it would be most unlikely for a SHB to point close to the observer.

Since 1997 only two theoretical models of GRBs and their afterglows (AGs) —the standard fireball (FB) model [6] and the cannonball (CB) model [7]— have been extensively used to interpret the innumerable observations. Advocates of both models have

([1]) SHB stands for "Short Hard Burst", a sub-class of gamma-ray bursts (GRBs) lasting less that $\sim 2$ s and whose photons generally have comparatively large energies.

 

claimed to fit the data very well. But the two models were originally and still are quite different in their basic assumptions, despite the repeated replacements of key assumptions of the "standard" FB model (but not its name) with assumptions underlying the CB model —*e.g.*, supernovae (SNe) of Type Ia as progenitors of most GRBs, highly collimated ejecta made of ordinary matter, as opposed to spherical or conical shells of an $e^+ e^- \gamma$ plasma, "jets" not necessarily seen almost on axis. For a recent extensive discussion of the observational tests of FB and CB models, see [8].

Significantly, and in contrast to the FB model(s), the CB model has made many successful *predictions*. Among them, the large polarization of the GRB's $\gamma$ rays [9], the precise date at which the supernova associated with GRB030329 would be discovered [10], the complex "canonical" shape [11] of many GRB afterglows [12, 13], the correlations between various prompt(2) observables [14, 15] or with AG observables [16].

The SHB170817A event is an optimal case to tighten the discussion of the comparisons between different models of GRBs. The question of the apparently superluminal motion of the source of its afterglow, discussed in chapter **5**, is particularly relevant.

## 2. – The cannonball model

The CB model is based on a direct analogy of a phenomenon that is abundantly observed but poorly understood: the relativistic ejecta emitted by quasars and microquasars. The model [9] is illustrated in fig. 1. In it, bipolar jets of highly relativistic ordinary-matter plasmoids (a.k.a. CBs) are assumed to be launched as a compact stellar object is being born. SNe of Type Ic (the broad-line stripped-envelope ones) thus generate long-duration GRBs as the electrons in a CB raise the photons in the SN's "glory" by Inverse Compton Scattering (ICS) into a forward-collimated narrow beam of $\gamma$-rays [9].

Similarly, in the CB model, mergers of two neutron stars (NSs) or a NS and a black hole (BH) give rise to SHBs. In this case, the role of the glory of light is played by a Pulsar Wind Nebula (PWN) powered by the spin-down of a newly born rapidly-rotating pulsar —suggesting that most SHBs are produced by NS mergers yielding a NS remnant rather than a black hole [17, 18]. SN-less GRBs are produced in high-mass X-ray binaries, as a NS accreting mass from a companion suffers a phase transition to a denser object. Finally X-ray flashes (XRFs) and some X-ray transients are simply GRBs observed from a relatively large angle relative to the CBs' emission axis.

## 3. – Is SHB170817A noteworthy all by itself?

A first question regarding SHB170817A is whether or not it is a typical SHB. The CB model provides a strongly affirmative answer, in all respects. A first test employs the correlations between observables predicted by this model.

Let $\gamma_0$ be the initial Lorentz factor with which a CB is launched. Its electrons inverse-Compton-scatter the ambient photons they encounter. This results in a $\gamma$-ray pulse of aperture $\simeq 1/\gamma_0 \ll 1$ around the CB's direction. Viewed by an observer at an angle $\theta$ relative to the CB's direction, the individual photons are boosted in energy by a Doppler factor $\delta_0 \equiv \delta(t=0) = 1/[\gamma_0\,(1-\beta_0\,\cos\theta)]$ or, to a good approximation for $\gamma_0^2 \gg 1$ and $\theta^2 \ll 1$, $\delta_0 \simeq 2\gamma_0/(1+\gamma_0^2\theta^2)$. The ICS of photons of energy $\epsilon$ by a CB boosts their energy, as seen by an observer at redshift $z$, to $E_\gamma = \gamma_0\,\delta_0\,\epsilon/(1+z)$. Thus, the peak energy,

(2) *Prompt* customarily refers to quantities measured prior to the afterglow phase.

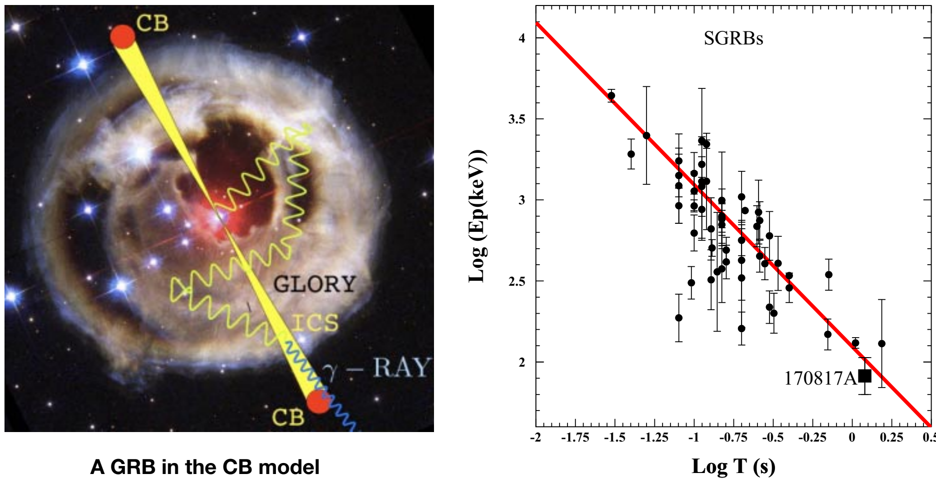


Fig. 1. – Left: Electrons in a CB Compton scatter photons in the glory of a newly-born compact object, launching them forward as a narrow beam of $\gamma$ rays. Right: Comparison between the CB-model's correlation $E_p \propto 1/T_p$ and the data in GCN circulars for resolved pulses of SGRBs.

$E_p$, of their time-integrated energy distribution satisfies $(1+z)\,E_p \approx \gamma_0\,\delta_0\,\epsilon_p$, with $\epsilon_p$ the characteristic or peak energy of the initial photons (for the glory of a SN $\epsilon_p = \mathcal{O}(1)$ eV, for a PWN $\epsilon_p = \mathcal{O}(1)$ keV). The peak-time of a single $\gamma$-ray pulse obeys $T_p \propto (1{+}z)/\gamma_0\,\delta_0$. SHB170817A, being a one-peak event, is a good case to study these observables. Indeed, one of the simplest CB-model predictions is the $[E_p, T_p]$ correlation $E_p \propto 1/T_p$. In the righthand side of fig. 1 this correlation is compared with the values of $E_p$ and $T_p$ in the GCN circulars [19] for resolved SGRB pulses. SHB170817A is where it should be.

The nearly isotropic distribution (in the CB's rest frame) of a total number $n_\gamma$ of IC-scattered photons is beamed into an angular distribution $dn_\gamma/d\Omega \approx (n_\gamma/4\,\pi)\,\delta^2$ in the observer's frame. Consequently, the isotropic-equivalent total energy of the photons satisfies $E_{iso} \propto \gamma_0\,\delta_0^3\,\epsilon_p$. Hence, both ordinary long- and short-duration GRBs, viewed most probably from an angle $\theta \sim 1/\gamma$ (for which $\delta_0 \sim \gamma_0$), should satisfy [14] the "Amati" correlation [20], $(1+z)\,E_p \propto [E_{iso}]^{1/2}$, shown in on the left of fig. 2. Far off-axis GRBs $[\theta^2 \gg 1/\gamma^2$, so that $\delta_0 \approx 2/(\gamma_0\,\theta^2)]$, have a much lower $E_{iso}$, and satisfy $(1+z)\,E_p \propto [E_{iso}]^{1/3}$. As shown on the right of fig. 2, SHB170817A "is right where it should be", since, as we shall see, it was indeed seen far off-axis. The correlations we discussed are trivial consequences of GRBs being narrow beams of $\gamma$ rays seen somewhat off-axis. They are not predictions of FB models. In them, the jetted beams were generally assumed to be seen on-axis, at least up to the observation of SHB170817A.

A more detailed test concerning the run-of-the-mill nature of SHB170817A is the shape of its single pulse of $\gamma$'s. The light "reservoir" that a CB will Compton up-scatter (a SN glory or a PWN) has a thin thermal bremsstrahlung spectrum and a number density distribution decreasing with distance to the CB source as $1/r^2$ [21]. With these inputs it is painless to derive a two-parameter simple expression that provides excellent descriptions of pulse shapes [22]. A well measured GRB pulse is shown on the left of fig. 3. The pulse of SHB170817A is on the right. Again, there is nothing atypical about it. The peak energy and peak time of this SHB are also the expected ones [8].

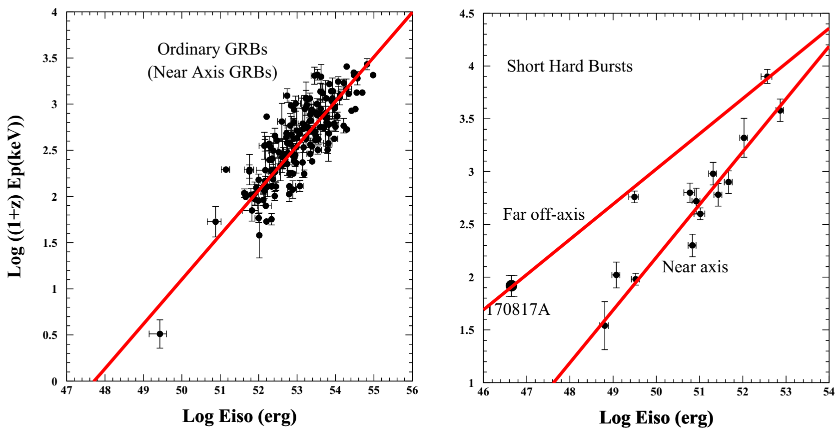


Fig. 2. – Left: The $[E_p, E_{iso}]$ correlation in GRBs viewed near axis. The line is the best fit, whose slope, 0.48±0.02, agrees with the CB model's prediction: 1/2. Right: The correlation in SHBs. The lines are the CB-model's predicted correlations.

In FB models [6] the GRB prompt pulses are produced by synchrotron radiation from shock-accelerated electrons in collisions between overtaking thin shells ejected by a central engine, or by internal shocks in the ejected conical jet. Only for the fast decline phase of the prompt emission, and only in the limits of very thin shells and fast cooling, falsifiable predictions have been derived [31-33]. They result in a power law decay $F_\nu(t)\propto(t-t_i)^{-(\beta+2)}\nu^{-\beta}$, where $t_i$ is the beginning time of the decay phase, and $\beta$ is the spectral index of prompt emission. The observed decay of the SHB170817A pulse could only be reproduced by adjusting a beginning time of the decay and replacing the constant spectral index of the FB model by the observed time-dependent one [31].

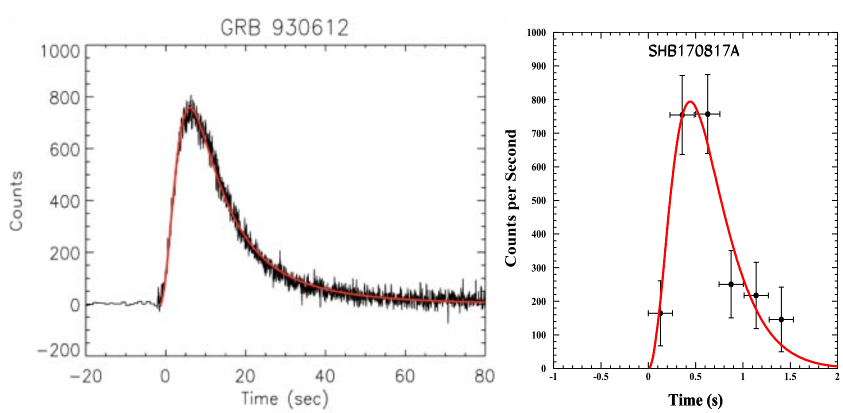


Fig. 3. – Left: The pulse shape of GRB930612 measured with BATSE aboard CGRO and the best CB-model fit to re-bined data [23]. Right: The pulse shape of SHB170817A measured with the Fermi-GBM [25-29] and its CB-model best fit, with $\chi^2/\mathrm{dof}=0.95$ [23].

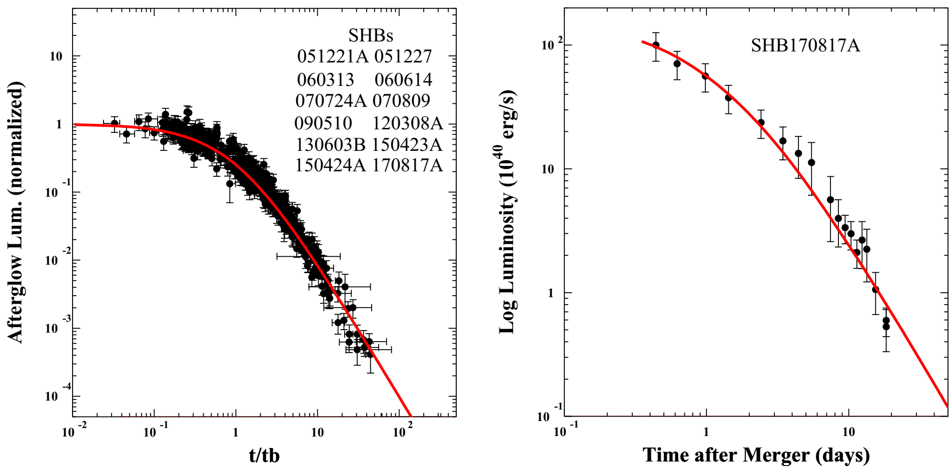


Fig. 4. – Left: Comparison between the normalized light curve of the X-ray AG of 11 SHBs with a well sampled AG measured with Swift's XRT [36] during the first couple of days after burst and the predicted universal behavior of [35]. Right: Comparison between the observed [37] bolometric light curve of SHB170817A and the prediction of [35], assuming the presence of a milli-second pulsar with $L(0)=2.27\times 10^{42}$ erg/s and $t_b=1.15$ d. The fit has $\chi^2/\mathrm{dof}=1.04$.

## 4. – The afterglow of GRBs and SHBs

In the CB model the afterglow of GRBs is due to synchrotron radiation (SR) from the electrons in a CB that is traveling and decelerating as it interacts with the interstellar medium (ISM), previously fully ionized by the GRB's $\gamma$ rays. The electrons radiate in the turbulent magnetic field generated by the merging plasmas, whose energy density is assumed to be in equilibrium with the kinetic energy brought (in the CB's rest system) by the ISM constituents. With these inputs, the model provides an excellent and predictive description of the temporal and spectral dependence of GRB afterglows.

The CB-model's description of the early AGs of SHBs and "Supernova-less" GRBs differs from the one of ordinary (SN-generated) GRBs. It is simply the isotropic radiation from a pulsar wind nebula (PWN), powered by a newly born rapidly-rotating pulsar, and has an expected luminosity [34] satisfying $L(t,t_b)/L(t=0)=(1+t/t_b)^{-2}$, with $t_b=P(0)/2\,\dot{P}(0)$, where $P(0)$ and $\dot{P}(0)$ are the pulsar's initial period and its time derivative. This *universal behaviour* [35] describes well the AG of all the SN-less GRBs and SHBs with a well sampled AG during the first few days after burst. This is demonstrated on the left of fig. 4 for the twelve SHBs [17] from the Swift XRT light curve repository [36] that were well sampled in the mentioned period. The bolometric light curve of SHB170817A [37] is shown on the right of fig. 4. The two-parameter [$L(0)$ and $t_b$] CB-model fit is excellent. SHB170817A, once more time, is not deviant.

**4·1.** *The late-time afterglow of SHB170817A.* – The PWN-powered early AG decreases with time extremely fast and is eventually overtaken, in the CB model, by the synchrotron radiation from CBs. In the case of SHB170817A, the AG was very well observed up to extremely late times: almost three years [38]. To discuss this subject within the page-number limit I have to skip details contained in [8]. For a CB travelling in a constant-density ISM, the spectral energy density of its AG is $F_\nu(t,\nu)\propto t^{0.72\pm 0.03}\nu^{-0.56\pm 0.06}$, where

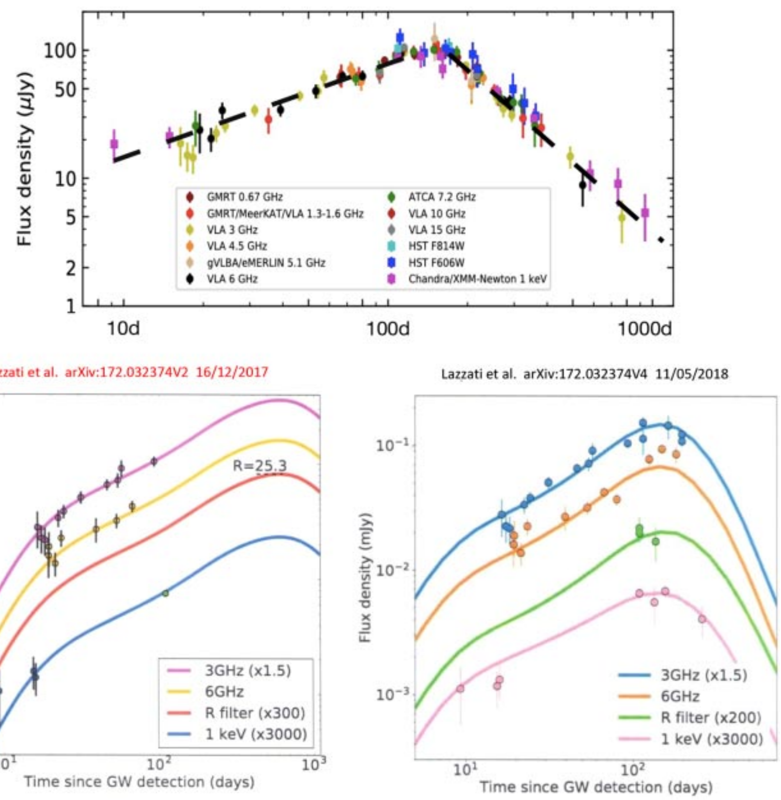


Fig. 5. – Up: Radio, optical and X-ray observations of the AG of SHB170817A, fig. 2 of [38]. The radio light curve is scaled to 3 GHz using the spectral index $-0.584$. The early-time trend expected in the CB model is the rising black-dashed line. The late-time trend, also black-dashed, is for an assumed $1/r^2$ ISM density decline encountered by the CB after day $\sim 150$. Down Left: Best fit light curves of an off-axis structured jet model [41] before December 2017 (first version of [41] arXiv dated 171217). Down, Right: Best fit light curves up to April 2018, obtained from a structured jet model [42]. Reported in version 4 of [41], arXiv dated 180511. Reprinted with permission from Lazzati D. *et al.*, *Phys. Rev. Lett.*, **120** (2018) 241103, `https://doi.org/10.1103/PhysRevLett.120.241103`. Copyright (2018) by the American Physical Society.

I used the observed [39] spectral index $0.56\pm0.06$, which extends from the radio (R) band, through the optical (O) band, to the X-ray band. If the CB moves out into a wind-like ISM density distribution (proportional to $r^{-2}$) $F_\nu(t,\nu) \propto t^{-2.12\pm0.06}\nu^{-0.56\pm0.06}$. These results agree with the observations [38], as shown in the upper part of fig. 5.

**4˙2.** *FB-model interpretations of SHB170817A.* – Soon after the discovery of the late-time AG of SHB170817A, many FB model best fits to the initially rising light curves were published. They involved completely different models and multiple best-fit parameters (*e.g.*, [40] and references therein). As new observations were made, the proponents of FB model(s) put to use their large flexibility, see, *e.g.*, the arXiv versions 1-4 of [41]. All these models —with a chocked jet cocoon, conical or structured jets at $\theta=0$, or not— failed to correctly predict the subsequent data. This is demonstrated in the lower left part of fig. 5. When the AG break around day 150 and its subsequent fast decline were observed, the structured jet model with its dozen or so adjustable parameters had no problem to accommodate this behavior, see the lower right part of fig. 5.

Neither could the CB model foretell the change of slope in fig. 5, but its explanation is simple. It only required changing the ISM density from a constant to a $1/r^2$ behavior, a one-parameter change, consistent with the CB starting to exit the galaxy.

## 5. – The CB's superluminal velocity in GRBs and SHBs

The first observation of an apparent superluminal velocity of a source in the plane of the sky was reported [43] in 1902, and since 1977 in many observations of jets launched by quasars, blazars, and micro-quasars. The interpretation of this kind of observations within the framework of special relativity was provided by Paul Courderc in 1939 [44].

**5·1.** *The superluminally moving source of SHB170817A.* – The VLBI/VLBA observations of the radio AG [24] of SHB170817A provided images of an AG source escaping from the GRB location with superluminal celerity. Such a behavior in GRBs was predicted within the CB model [7] two decades ago [24]. Figure 1 of ref. [24] shows the displacement with time of a compact radio source by 2.68±0.3 mas between day 75 and day 230. In [24] this image is called "a jet". It is in fact a time-lapse capture of the moving CB emitted (approximately) towards us by the fusion of the neutron stars.

A source with a velocity $\beta\, c$ at redshift $z$, viewed from an angle $\theta$ relative to its direction of motion and recorded by the local arrival times of its emitted photons has an apparent velocity in the plane of the sky: $V_{app} = \beta\, c\, \gamma\, \delta \sin\theta/(1+z)$. In the excellent $\beta = 1$ approximation one may write

$$V_{app} \approx \frac{c\,\sin\theta}{(1+z)\,(1-\cos\theta)} \approx \frac{D_A\,\Delta\theta_s}{(1+z)\Delta t}\,, \tag{1}$$

which we have also expressed in terms of observables: $\Delta\theta_s$ is the angle by which the source is seen to have moved in a time $\Delta t$; $D_A = 39.6$ Mpc is the angular distance (for the local value $H_0 = 73.4 \pm 1.62$ km/s Mpc obtained from Type Ia SNe [45]) to SHB170817A and its host galaxy NGC 4993, at $z = 0.009783$ [2]. The location of the VLBI-observed source —which moved $\Delta\theta_s = 2.70 \pm 0.03$ mas in a time $\Delta t = 155$ d (between days 75 and 230)— implies $V_{app} \approx (4.0 \pm 0.4)\, c$, which, solving for the viewing angle $\theta$ in eq. (1), results in $\theta \approx 27.8 \pm 2.9$ deg. This value agrees with $\theta_{\rm GW} = 25 \pm 8$ deg, the angle between the direction to the source and the rotational axis of the binary system, obtained from —only— gravitational wave observations [46], for the same $H_0$ [45].

More strikingly, one can invert the order of the previous concordance. If the value of $\theta_{\rm GW}$ implied by the GW observations is input in eq. (1), the result is a correct prediction of the magnitude of the observed superluminal velocity. So simple!, this is a "multi-messenger" collaboration working at its best.

**5·2.** *The two superluminally moving sources of GRB030329.* – This GRB was the subject of a unique open controversy between advocates and critics of FB and CB models.

As mentioned in the Introduction, the CB model was used to fit the early AG of GRB030329 and to predict the discovery date of its associated SN, SN2003dh. This being a two-pulse GRB, the fits to its $\gamma$ rays and to its two-shoulder AG curve consequently involved two cannonballs. The prediction of the amount of their superluminal motions, based on the approximation of a constant ISM density, turned out to be wrong [47]. Subsequent observations of the AG showed a series of very clear re-brightenings, interpreted in the CB model as encounters of the CBs with ISM over-densities [48]. Corrected by the consequent faster slow-down of the CBs' motion, the new CB-model results were not a prediction, but were not wrong (see [49] and its fig. 2 for details not mentioned here).

The authors of [47] analized their data in terms of a single radio source, in spite of the fact that, with a significance of $20\,\sigma$, they saw two: *Much less easy to explain is the single observation 52 days after the burst of an additional radio component 0.28 mas northeast of the main afterglow.* Whether there was one or two sources of the AG is the crux of the (factual) clash between FB- and CB-model interpretations [49].

Quite forcefully Bloom and collaborators [51] stated: *Very Long Baseline Array imaging of the compact afterglow was used by Frail (2003)* [47] *to unequivocally disprove the cannonball model for the origin of GRBs.* However, referring to their "second source" the authors of [47] admitted: *This component requires a high average velocity of 19c and cannot be readily explained by any of the standard models. Since it is only seen at a single frequency, it is remotely possible that this image is an artifact of the calibration.*

As for this second source, will the dictum *seeing is believing* be rejected, with the image of a moving CB in fig. 1 of ref. [24] somehow serving to disprove the cannonball model?

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