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Abstract :

The cannonball model of GRBs is very overt (and, thus, falsifiable) in its hypothesis and results: all the considerations I review are based on explicit analytical expressions derived, in fair approximations, from first principles. The model provides a good description of *all* the data on *all* GRBs of known redshift, has made correct predictions, and is unprecedentedly self-consistent, simple and successful.

The cannonball (CB) model of GRBs [8, 9, 2, 5] is based on **our** ignorance, for **we** (its authors) do not understand, e.g.: how the GRB engine works, how core-collapse supernovae (SNe) eject their ejecta, the transport of angular momentum in processes of collapse and/or accretion, relativistic magnetohydrodynamics, the relativistic ejections in quasars and micro-quasars... Thus, we base our starting hypothesis on analogy with the *observations* of quasars and μ -quasars, overlooking current numerical simulations of these phenomena¹. Quasars and μ -quasars appear to expell relativistic plasmoids when matter accretes abruptly from a disk or torus orbiting them. We assume the GRB engine to be similar: relativistic CBs are emitted axially from the recently made compact object in a core-collapse SN, as matter that has not been expelled as a SN shell (SNS) falls back [12] to constitute an unstable disk. Most indications are that the plasmoids are made of ordinary matter, not some fancier substance such as e^+e^- pairs with some finely-tuned “baryon-load”, as assumed in the conventional GRB scenarios: fireballs or their progeny (hereinafter “the standard model (SM)”); for a balanced review, see [13]).

Crossing the SNS with a large Lorentz factor γ , the surface of a CB is collisionally heated to keV temperatures and the radiation it emits when it reaches the transparent outskirts of the shell—boosted and collimated by the CB’s motion—is a single γ -ray pulse in a GRB. The cadence of pulses reflects the chaotic accre-

tion processes and is not predictable, but the individual-pulse temporal and spectral properties are. One example of γ -ray light-curve is given in Figure 1, for the single pulse of GRB 980425, the closest-by GRB on known redshift z . An example of spectrum is given in Fig-

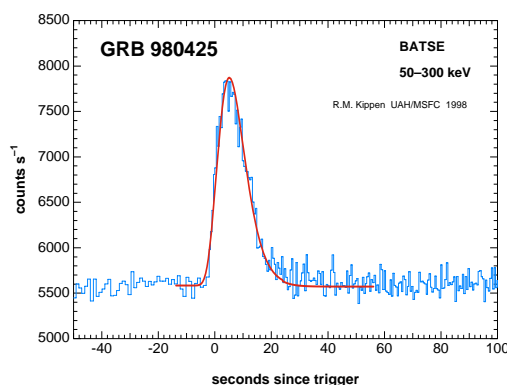


Figure 1 : Temporal shape of GRB 980425

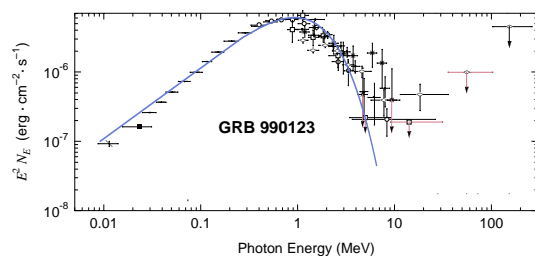


Figure 2 : $E^2 dn_\gamma/dE$ spectrum of GRB 990123

ure 2, for the most energetic recorded GRB of known z . The high-energy tail is not well reproduced by our simplified quasi-thermal model [9]; it should be flatter. This is not surprising: we did not take into account that a CB in its rest system is bombarded by SNS particles of high γ , which cannot be instantaneously thermalized. The low-energy part of

¹ The definition #1.a of “simulation” in the OED is: “The action or practice of simulating, with intent to deceive; false pretence, deceitful profession”.

the spectrum, in this and other GRBs, behaves as $E^2 dn_\gamma/dE \approx E^1$, in agreement with the CB-model’s prediction (the standard fireball scenario inescapably predicts a slope disagreeing with observation by $\sim 1/2$ unit [14]). A long list of general properties of GRB pulses (e.g., that they are narrower at high than at low energy) is reproduced in the CB-model, in which, unlike in the SM, the GRB’s γ s are of thermal (as opposed to synchrotron) origin [9].

From our analysis of GRBs we deduced that the observed γ -ray fluences and individual- γ energies imply that CBs have typical Lorentz factors $\gamma \sim 10^3$ and are only observable for angles θ (between the jet axis and the observer) of $\mathcal{O}(10^{-3})$. For such a small viewing angle, the universal rate of GRBs and that of core-collapse SNe are comparable: *we are defending the extreme view that a good fraction of such SNe emit GRBs*. The mass and baryon number (N_{CB}) of a CB are typically a fraction of those of our planet: peanuts, by stellar standards.

In GRS 1915+105 the observations are compatible with the ejecta expanding laterally with a transverse velocity (in their rest system) comparable to $c/\sqrt{3}$. In many quasars, such as Pictor A, the ejecta appear to travel long distances without expanding laterally. In the analysis of the radiation from these sources, as in the CB model which they inspire, γ and θ (plus the total energy in the ejecta) are the parameters needed to describe the observations. In the old fireball model of GRBs the ejecta were spherical. Dar and collaborators have insisted for a long time that this implied too large a total energy, and that GRBs should be “jetted” emissions from SNe [19]. Fireball advocates have slowly let fireballs become firecones [17] or, more properly, firetrumpets: jets of material funneled in a cone of initial opening angle (also called) θ , that increases as the ejecta encounter the interstellar medium (ISM), see Figure 3. For years the modellers placed the observer precisely on-axis, so that all detected GRBs would point to us: an *anthropoaxial* view. More recently, the SM view is evolving towards the realization that the observing angle *also* matters [18], a step in what

I believe to be the right direction: the observation angle is the *only* one that matters.

We assume CBs, like the observed ejecta in quasars and μ -quasars, to contain a tangled magnetic field. In that case, as they plow through the ISM, they gather and re-scatter its constituent protons. The re-emitted protons exert an inwards pressure on a CB which counters its expansion. In the approximation of isotropic reemission in the CB’s rest frame and constant ISM density n_p , we explicitly find that, in a matter of observer’s minutes, a CB —faithfull to its name— reaches an asymptotic radius R of $\mathcal{O}(10^{14})$ cm. In the same approx-

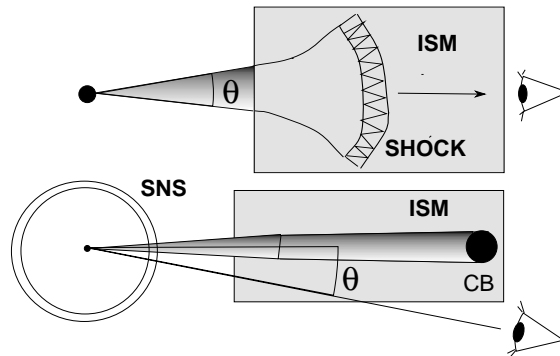


Figure 3 : Standard and CB-model geometry.

imation we may compute the magnetic field that sustains the inwards pressure of the outgoing protons ($B \sim \mathcal{O}(\text{a few})$ Gauss) and derive the explicit law of CB deceleration in the ISM, that depends on the initial $\gamma = \gamma_0$ as they exit the SNS and a “deceleration” parameter $x_\infty = N_{CB}/(\pi R^2 n_p)$. CBs decelerate to $\gamma(t) = \gamma_0/2$ in a journey of x_∞/γ_0 length, typically of $\mathcal{O}(1)$ kpc.

A CB exiting a SNS soon becomes transparent to its own enclosed radiation. At that point, it is still expanding and cooling adiabatically and by bremsstrahlung. The brems spectrum is hard and dominates the early X-ray AG, with a fluence of predictable magnitude decreasing with time as t^{-5} . An example of how well this describes early X-ray AGs is shown in Figure 4. All X-ray AGs are compatible in magnitude and shape with this prediction. In the “internal-external shock” SM both

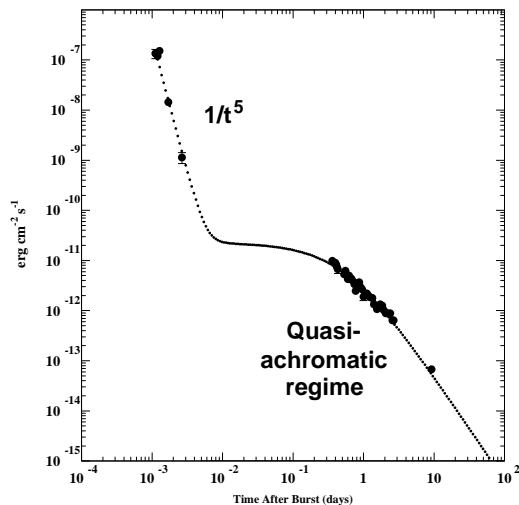


Figure 4 : The Xray AG of GRB 010222 [2]

the GRB proper and its AG are due to synchrotron radiation, internal collisions between shells result in the GRB, the external collision of all shells with the ISM begets the AG. Internal shocks are inefficient at creating internal energy, e.g.: two shells of mass m and Lorentz factors γ and $\gamma/2$ coalesce to produce an object of mass $\sim 2m(1 + 1/16) \sim 1.06(2m)$, so that, in $e-p-B$ energy equipartition, $\sim 2\%$ of the energy would end up in synchrotron-radiating electrons. The external shock (a collision of a composite object of mass M and Lorentz factor Γ with the ISM at rest) is overwhelmingly more efficient: a third of all the energy $M\Gamma c^2$ is available! It is difficult to understand why the integrated energy in a GRB is much *larger* than in the AG [13], why the X-ray light curves initially descend the way they do, and how the discovery of such patently misbehaving AGs could be hailed as a great success of the SM (the real difficulty lies in imagining *any* GRB model *without* an AG; try!).

The optical AGs of *all* GRBs of known z are also well described in the CB model. They, and the late X-ray AGs, are due to synchrotron radiation by the electrons that the CB gathers in its voyage through the ISM.

The optical AGs for which the data start very early after the GRB are particularly interesting. The AG of GRB 990123, in Figure 5, is an example. In these early AGs we detect—in

the CB model, in which the observer’s “clock” runs at 10^{-6} to 10^{-5} the rate of a CB’s travel-time—the CBs plowing through the $\sim r^{-2}$ density-profile of the “wind” ejected by the associated SN. This implies an early decline $\propto t^{-2}$, whose normalization can also be estimated, also agreeing with the data. In the SM

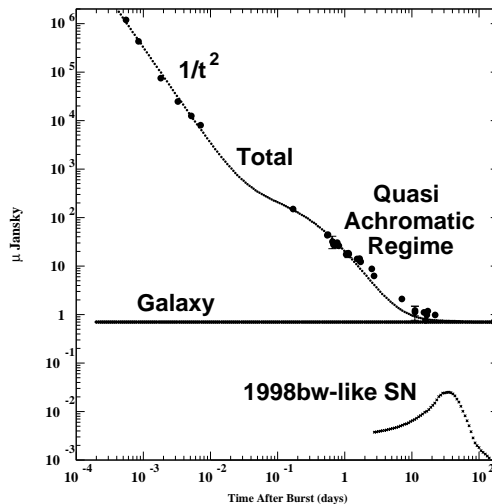


Figure 5 : The R-band AG of GRB 990123 [2]

the absence of “windy” signatures is a problem, to the extreme that, after quoting some 20 earlier failures: “Unfortunately, until now there has been no clear evidence for a wind-fed circumburst medium” (CBM), these SM-devotee authors [16] thus continue to report their personal feelings about GRB 011121: “to our delight [we] have found a good case for a wind-fed CBM”; see [11] for comment.

In the CB model, all long-duration GRBs are associated with SNe compatible with a (properly transported) SN 1998bw [7], the one associated with the very close-by GRB 980425. Naturally, “standard candles” do not exist, but this one, so far, is doing a good job. Half of the score of GRBs of known z are too far to see their associated SN and, *when the SN should not be seen, it was not seen*. Analyzed in the CB model, the other half have either indications or (as z decreases) incontrovertible evidence for such a SN: *when the SN could be seen, it was seen*. This gave us confidence to *predict* how the associated SN would appear in

the case of GRB 011121. We used in [3] the first 2 days of R-band data to fit the parameters describing the CBs' contribution to the AG. Extrapolating it in time, we predicted explicitly how the AG would evolve, and we concluded: *the SN will tower in all bands over the CB's declining light curve at day ~ 30 after burst.* The comparison with the data [4], gathered later, is shown in Figure 6. The SN spectrum is slightly bluer than that of 1998bw, but not significantly so. In the SM, it is not possible to reproduce the previous exercise because the AGs (unlike the smoothly-vaying data) have “breaks”. The early data on GRB 011121 do not tell you where the break “is”: they cannot be extrapolated. That may help explain why the same SM-abiding observers first concluded that this GRB had no associated SN [1], the day after that it did [15], to compromise finally into half of a SN1998bw-like signal [16].

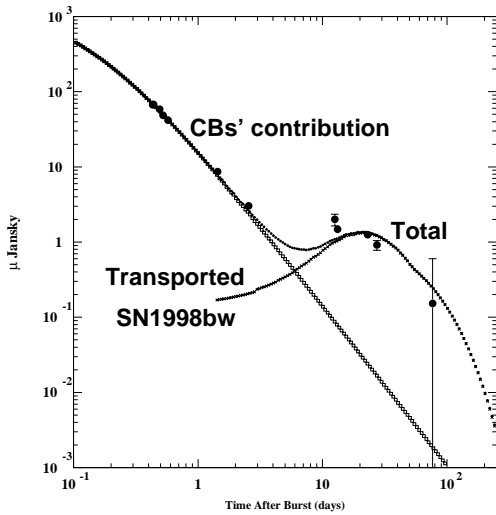


Figure 6 : R band AG of GRB 011121 with the galaxy contribution subtracted [4].

In the CB model [5] the spectrum of electrons in the CB, accelerated by its enclosed magnetic maze and cooled by synchrotron radiation, has an *injection bend* at the energy $E_b = m_e c^2 \gamma(t)$ at which a CB would, in its rest system, see the ISM electrons arrive, with $\gamma(t)$ the instantaneous CB Lorentz factor, extractable from the fit to the AG light-curve. The emitted synchrotron radiation has

a corresponding bend at a frequency (in the CB's frame) $\nu_b = 0.2175 \gamma(t)^2 \nu_L$, with ν_L the Larmor frequency in the CB's magnetic field, whose magnitude is also explicit and evolves as $B(t) \propto \gamma(t)$, so that $\nu_b \propto \gamma(t)^3$. Prior to absorption corrections, the synchrotron fluence in a CB's rest system is:

$$f_{sync} \equiv \nu \frac{dn_\gamma}{d\nu} \propto \frac{[\nu/\nu_b]^{-1/2}}{\sqrt{1 + [\nu/\nu_b]^{(p-1)}}} \quad (1)$$

with a predicted $p \approx 2.2$, in agreement with all the data on relatively late optical AGs, at which time $\nu \gg \nu_b$ and $f_{sync} \propto \nu^{-\alpha}$ with $\alpha = p/2 \approx 1.1$ (it is easier to extract this index from fits to the AG light-curve than from the spectra, which are beset by absorption corrections). The explicit interpolating form of Eq. 1 is a guess, but the existence and explicit time-dependence of the injection bend are bold conclusions, that need to be confronted with data. Getting a bit ahead of myself, I show in Figure 7 a typical predicted spectrum, in the observer's frame. The figure shows how

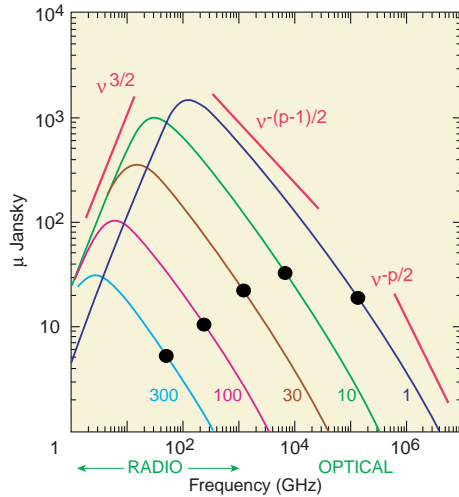


Figure 7 : Typical predictions for the CB model's GRB spectra, at times from 1 to 300 days. The peak frequencies correspond to CB self-opacities of $\mathcal{O}(1)$. The black dots are the location of the injection-bend frequency in the synchrotron radiation [5].

the predicted location of the spectral bend in frequency diminishes with time. Measured around a fixed frequency, a spectral slope may be time-dependent: $\alpha = (p - 1)/2 \approx 0.6$ before the “passage” of the injection bend and

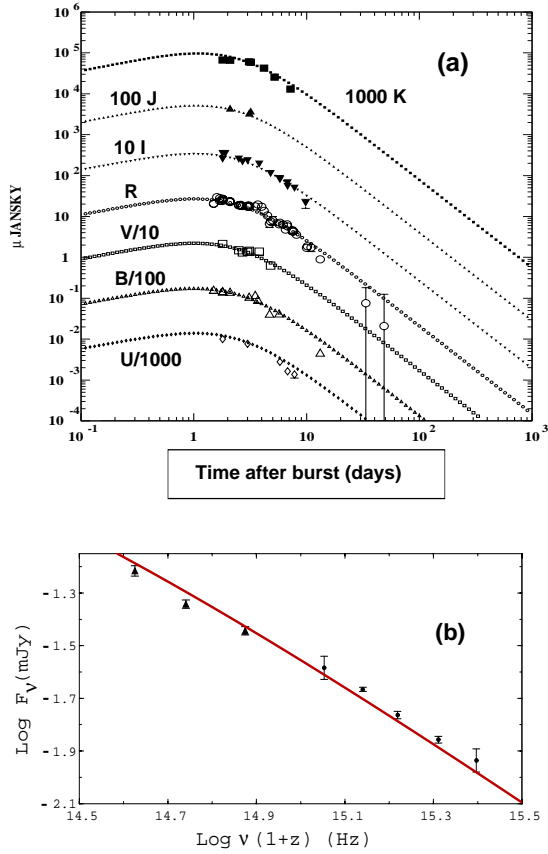


Figure 8 : GRB 000301c. (a) (Galaxy-subtracted) CB fit to optical light curves in all bands. (b) Predicted spectrum at $t \sim 3$ days [5].

$\alpha = p/2 \approx 1.1$ after it. In the 7 cases of GRBs with sufficient data to do this test, the agreement with expectations is good (the errors are often large). The complementary test is to look at a narrow-band spectrum when the bend is crossing or is nearby, so that the predicted slope would be neither of the extremes. A good case, with insignificant absorption, is GRB 000301c. From its observed optical light curves, fit to the CB model as in Figure 8a, we extract the AG parameters (normalization, θ , γ_0 and x_∞) needed to predict $\nu_b(t)$ and the spectral shape at a given time. The results at $t \sim 3$ days are shown in Figure 8b (the normalization is borrowed from the data but the slightly curving slope is a *prediction*).

In the radio domain, self-absorption in the CB is important. The dominant mechanism is free-free attenuation, characterized by a single parameter ν_a in the opacity, that behaves as $\tau_\nu = (\nu_a/\nu)^2(\gamma(t)/\gamma_0)^2$. Absorption is re-

sponsible for the turn-around of the spectra in Figure 7. All observed spectra agree well, in spite of the scintillations in the radio, with this figure, fit in each case to the specific GRB. The overall fits to the light-curves and spectra in all bands involve the four parameters mentioned earlier plus the *single* “radio” parameter ν_a (the situation is in stark contrast with the SM model fits, that are multiple-choice and involve many parameters in the spectral description, sometimes re-fit for each particular observational time). The complete description of the radio AG requires the inclusion of two effects that introduce no extra parameters: a “cumulation factor” for the electrons that emit the observed radio frequencies (it takes time for the ISM electrons gathered by the CB to cool to the radio-emitting energies) and an “illumination and limb-darkening” factor taking into account that the CBs are viewed relativistically (an observer would “see” almost all of the 4π surface of a spherical CB). The most complete broad-band data are perhaps those of GRB 991208. In Figure 9 I show its spectrum between 5 and 10 days after burst.

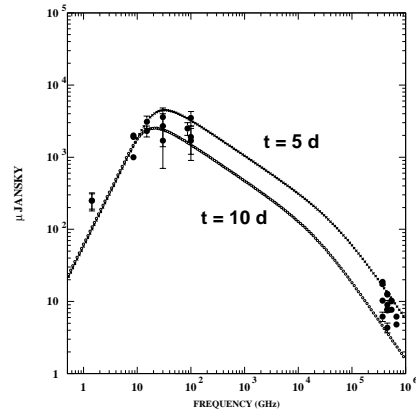


Figure 9 : CB-model fit to the broad-band spectrum of GRB 991208 at $t = 5$ to 10 days [5].

To give an example of radio light curve I choose the most interesting of all GRBs: 980425, at a tiny redshift of $z = 0.0085$; see Figure 10 [5]. In the CB model, this GRB and its associated SN1998bw are **not** exceptional. Because it was viewed at an exceptionally large angle (~ 8 mrad), its γ -ray fluence was comparable to that of more distant GRBs, viewed

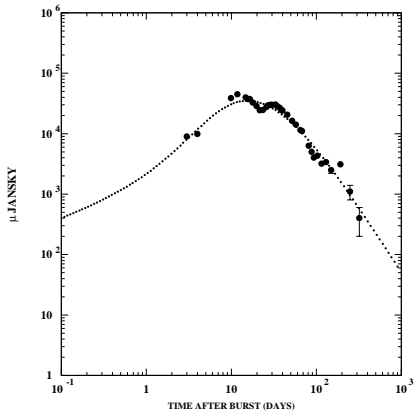


Figure 10 : 4.8 GHz light curve of GRB 980425.

at $\theta \sim 1$ mrad. That is why its optical AG was dominated by the SN, except for the last measured point [8]. The X-ray AG of its single CB (as in Figure 1) is also of “normal” magnitude, it is **not** emitted by the SN, and its fitted parameters allowed us to predict successfully the magnitude of the cited last optical point [2]. The normalization, time and frequency dependence of the radio AG of this GRB are also “normal”, and due to the CB, **not** the SN [5]. SN1998bw, deprived of its “abnormal” X-ray and radio emissions (which it did not emit!), loses most of its “peculiarity”.

The analysis of the radio scintillations of pulsars is one way to measure their sky-projected velocities, in agreement with proper-motion results. For cosmological GRBs, the sky angular velocity of their CBs happens to be comparable to that of the much slower and closer-by Galactic pulsars. Perhaps, then, the analysis of GRB radio oscillations may result in a measurement of their apparent velocities, which are “hyperluminal”: $v_T = \mathcal{O}(10^2) c!$ [5].

I have not discussed the mounting evidence for X-ray lines in GRB AGs. The results [6] are quite intriguing: the alleged lines are at the positions *predicted* [10] in the CB model.

What are the CB-model’s limitations? We contend that CBs are emitted at a time $t_{CB} = \mathcal{O}(1)$ day after the parent-star’s core-collapse [12]. That is the typical time for not-expelled and not-imploded stellar material to collapse back to the newly made compact object. It is peculiar that the GRBs typically last a small

fraction of t_{CB} , but the build-up of instabilities in the accretion disk may take long, while its episodes of “fall” may be brief. With $t_{CB} = \mathcal{O}(1)$ day, the SNS has moved to a distance that plays a role in our good description of the duration of GRB pulses. Yet, our model of the complex CB-SNS collisions may be naive: a better model will result in a smaller implied t_{CB} . As we move away from this early violent collision into the AG era, the CB model becomes simple and its results and success are robust. When we move even further and confront much of the GRB community of this planet... that is when the problems hit the roof.

References

- [1] Bloom J.S., et al. 2002 GCN Circ. 1274
- [2] Dado, S., Dar, A. & De Rújula, A., 2002, A&A 388, 1079
- [3] Dado, S., Dar, A. & De Rújula, A., astro-ph/0111468
- [4] Dado, S., Dar, A. & De Rújula, A., 2002, ApJL 572, L143
- [5] Dado, S., Dar, A. & De Rújula, A., submitted to A&A, (astro-ph/0204474)
- [6] Dado, S., Dar, A. & De Rújula, A., submitted to ApJ, (astro-ph/0207015)
- [7] Dar A., GCN Circ. 346
- [8] Dar A. & De Rújula A., astro-ph/0008474
- [9] Dar A. & De Rújula A., astro-ph/0012227
- [10] Dar A. & De Rújula A., astro-ph/0102115
- [11] Dermer, C.D., astro-ph/0204037
- [12] De Rújula, A., 1987, Phys. Lett. 193, 514
- [13] Ghisellini, G., astro-ph/0111584
- [14] Ghisellini, G. et al., MNRAS, 313, L1
- [15] Kulkarni S., et al. 2002 GCN Circ. 1276
- [16] Price P.A. et al. astro-ph/0203467
- [17] Rhoades J.E., ApJ 525, 737
- [18] Rossi, E. et al. astro-ph/0112083; Zhang, B. & Meszaros astro-ph/0112118; Salmonson J.D. & Galama astro-ph/0112298; Granot J. et al. astro-ph/0201322
- [19] Shaviv N.J., & Dar, A., 1995, ApJ 447, 863