On gamma-ray bursts and their biological effects : a case for an extrinsic trigger of the Cambrian explosion ?

J. E. Horvath

Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, R. do Matão 1226 (05508-900) São Paulo SP, Brazil

October 28, 2018

Abstract

We discuss some the effects of local gamma-ray bursts on the earth's atmosphere. A rough calculation of the fraction of ozone destruction by catalytic NO_x cycles is given, which in turn serves to argue how the large flux of gammas from these events would have indirectly provoked major extinction of living organisms. We give specific examples of these features, and tentatively identify the Cambrian explosion seen in the actual fossil record as an event caused by a GRB.

1 Introduction

A breakthrough in GRB astrophysics has been achieved by the observation of afterglows located ∼ few hours after the event with unprecedented positional accuracy $([1])$. The presence of absorption lines $([2, 3])$ in some of these afterglows has convinced most researchers that most (if not all) of the GRBs are extragalactic, although a through comprehension of the bursts is still far away since the sources have yet to be identified and the physics of the afterglows addressed (see, for example, $[4, 5]$). Nevertheless, we may now assert that a distance scale (and hence an energy scale) is available for "classical" bursts. Regardless of the specific source, it is now clear that the evidence points out to E_{γ} as high as $\simeq 10^{53} \ erg$ for the most energetic bursts $([6])$ if the gamma emission is isotropic. Given that such an extreme energy is quite difficult to obtain, and some convincing observational features have accumulated, the idea of a strongly beamed gamma flux has gained acceptance. A "standard reservoir" of $\sim 10^{51} erg$ has been advocated by Frail et al. [7] in a recent analysis.

While the study of distant, frequent bursts continues, the observations have undoubtedly risen a number of questions related to the occurrence of GRBs in the local universe. Thorsett [8] has discussed the effects of a close GRB on the earth's biosphere (see also [9] for a related discussion). The issue is timely since it has been shown that a burst must occur as often as $(0.3-40)$ Myr per L_{*} , depending on the evolution of the sources ([10]). Loeb and Perna [11] have further suggested that most of the HI supershells could be the remnants of GRBs. In fact some remnants must be found in a given normal galaxy, since they should not dissipate before \sim tens of Myr . The two gigantic shells reported in [12] in NGC 4631 are perhaps the most clear examples that \sim kpc-sized shells requiring $\sim 10^{54} erg$ of input energy are real since their identification is neater in external galaxies. The incidence of gamma rays from a GRB should be then seriously considered.

2 Gamma ray fluxes onto the earth and the ozone layer

Consider the case of the simplest, "standard candle" scenario for GRBs. We may estimate immediately the flux of gamma-rays at the typical band 30-2000 keV at the top of the atmosphere ϕ for an assumed energy in gamma-rays of $E_{\gamma} = 10^{51} \text{ erg}$. Since the true luminosity distribution function is still an unsettled question and there might be a considerable spread between the events, other possibilities should be considered.

Thorsett [8] pointed out that GRBs this close would (because of the huge gamma fluxes) should have produced deep effects on the biosphere. The destruction of a substantial amount of the ozone layer along a $\sim 10 s$ typical burst duration is the most obvious one, and seems inescapable since the $\geq 10^7 erg \, cm^{-2}$ gamma fluxes are in fact larger than the equivalent total chemical energy of the fragile ozone layer.

As discussed by Schramm and Ellis [13] (see [14] for the first discussion of a closely related event), several general features of the incidence of a huge gamma flux can be worked out with some confidence. For example, it is well established that the production of large concentrations of odd nitrogen NO_x is very harmful for the fragile ozone layer shielding the earth from solar UV radiation. The dominating catalytic reactions are

$$
NO + O_3 \rightarrow NO_2 + O_2 \tag{1}
$$

$$
NO_2 + O \rightarrow NO + O_3 , \qquad (2)
$$

since their efficiency of ozone destruction is high. The additional NO produced by the ionizing gamma flux will greatly enhance the penetration of solar UV because the former is expected to be much higher than the steady production by normal cosmic rays. The rate of production of NO (in $mol/cm²)$ is

$$
\xi = 10^{17} \phi_7 \left[\frac{13}{10 + y} \right],\tag{3}
$$

where $\phi_7 \equiv (\phi/10^7 erg \, cm^{-2})$ is the incident gamma flux scaled to a reference value, and the factor in brackets is the ratio of efficiencies of the steady production to the GRB flash in the stratosphere. Dividing ξ by the stratospheric column density and converting to parts per billion, we derive the abundance of NO produced by the GRB flash as the physical solution of a quadratic equation, very well approximated by

$$
y_{flash} \simeq 51\phi_7^{1/2} - 5. \t\t(4)
$$

Thus, the ratio of produced [NO] to the present ambient $[NO]_0$ is given by $X = (3 + y_{flash})/3 \sim 16\phi_7^{1/2}$. Such a great abundance of NO would remain in the stratosphere for a mean residence time of $\langle \tau \rangle = 4 \gamma r$, which is much larger than the homogenization time of the atmosphere. Thus, once produced by the flash the ozone layer would be affected for a period at least as large as the mean residence time of the catalyzer.

The approximate formula employed in [13] and [14] to estimate that reduction is

$$
\frac{[O_3]}{[O_3]_0} = \frac{(16 + 9X^2)^{1/2} - 3X}{2} , \qquad (5)
$$

expected to be accurate to within a numerical factor. It must be noticed that, according to the Ruderman-Schramm-Ellis results, the ozone destruction curve rises very rapidly with the gamma flux, presenting a "catastrophic" destruction which kills at least 90% of the present O_3 layer through NO enhancement for a fluence $\phi \geq 0.7 \times 10^7 \, erg \, cm^{-2}$. Actually it is highly likely that \sim tens percent O_3 destruction would already trigger massive biological death. Recent work by Gherels et al. [21] using a detailed radiative transport code arrives to a much lower figure of $\sim 10^8 erg cm^{-2}$ for a $\sim 35\%$ ozone depletion. Nevertheless, the important point to stress is that a large flux like this figure is actually expected from a galactic beamed burst which pointed to the earth if that ever happened.

In order to estimate some of the effects onto the biota we shall begin by calculating, using a simple attenuation model, the killing timescale of a marine unicellular organism population exposed to the UVB $(260-320 \ nm)$ radiation immediately after the burst. After a huge reduction of O_3 like the one discussed above one may assume the solar flux density to be essentially the value measured at the top of the atmosphere, some $0.2 W cm^{-2} \mu m$ on average. The mortality of single-cell organisms by UBV photons can be described ([15]) by

$$
\frac{N}{N_0} = 1 - (1 - \exp(-\kappa D))^m \tag{6}
$$

where N_0 is the original population, m is the number of absorbed photons needed to kill the cell, κ is a constant depending of the species and D is the dose here defined as $\int F_{\lambda} d\lambda$. This model can be immediately applied to

a marine population assumed to be distributed exponentially with a fixed depth scale z_0 (i.e. without considering day-night circulation) and having a spontaneous reproduction rate η . If N_s is the number of organisms at $z = z_0$ and the coefficient of attenuation for UVB photons in marine water is z_1 we find that the temporal evolution of this population at any depth will be given by

$$
N(z,t) = N_s \exp(-z/z_0) \exp[(\eta - \xi(z))t]
$$
\n
$$
(7)
$$

with $\xi(z) \simeq \kappa F_{\lambda 0} \Delta \lambda \exp(-z/z_1)$. Now we may ask which is the time for killing 90% of these organisms once the UVB flux starts to impact onto the sea surface, denoted as τ_{90} . If we normalize the mortality curve using the data from modern bacteria (i.e. Escherichia Coli), for which plenty of data is available, we obtain for this time $\tau_{90} = 0.4 \exp(z/z_1) s$. Therefore, it is concluded that simple marine organisms, and especially those capable of photosynthesis, will be killed almost instantaneously unless they can "hide away" at several tens of z_1 , in practice $\geq 100 \, m$ for a time as long as the healing of the ozone layer, which is certainly larger than most of the small marine organisms considered. Terrestrial organism behavior is much more difficult to model, although it has been known for fifty years that mammals would not survive longer than \sim 1s without ozone. Even though simple models may be oversimplified (they ignore all the detailed DNA repairing mechanisms and assume an unimpeded single value of the solar UV flux following the event), we believe that the essential points of a mass extinctions by a GRB are adequately illustrated and quantified beyond any reasonable doubt.

The gamma shower would have produced other rather unique catastrophes as well, all them contributing to the extinction of living beings. The production of $\sim 10^9$ tons of NO_x enhancing the acid rains and the screening effects of $NO₂$ to the sunlight (with possible dramatic cooling effects, see [16]) are just two of them. To address these issues properly, the actual possibility of a close GRB calls for a through study of the dynamical response of the biosphere to a large perturbation, since all the effects are deeply interwoven and it is quite difficult to isolate them due to their non-linear character.

3 A tentative association of a GRB with the Cambrian explosion

According to the picture above, it seems quite clear that the incidence of a gamma-ray burst beam onto the atmosphere would trigger a quite remarkable biological evolution pattern, yet to be precisely characterized. The natural question is whether we may associate a definite event to such an external cause, based on the existing evidence and a bit of extrapolation. As discussed above, the extinction of a large number of living species due to UVB action is, of course, a first necessary feature, but there are a few more related effects to consider. One is the fate of the *surviving* populations, since they are likely to be exposed to a large ultraviolet flux on average, a powerful force driving their further evolution through its action on the genetic material (hypermutation?). It is also important to have in mind that the surviving populations may be physically isolated from each other in relatively small ecosystems, a scenario that can be justified by the very nature of the catastrophic event. This situation is known to be favorable for rapid speciation, although it is not as certain whether a hypermutation rate drives an accelerated evolution [17]. The exposure of bacteria to UV light is known to have dramatic effects by exploding the cell and releasing bacteriophage genes, another feature that could have suddenly boosted the genetic exchange and cleared the ecosystem from very abundant, well-adapted organisms at the same time.

We suggest that the celebrated Cambrian explosion, ∼ 544 Myr ago may grossly match these features. It is now established that the oxygen levels were high enough at that epoch, and it is fair to assume an ozone layer essentially equal to the modern one. At the Proterozoic-Cambrian boundary and before the explosion itself, simple animals pertaining to the diploblastic Ediacaran fauna were suddenly extinct on a very short timescale; and the emergence of an extremely diversified fauna followed, suggesting some global event that could have triggered genetic experiments eventually leading to an exponential growth of the number of species during the early Cambrian age. While several intrinsic causes have been advanced to justify this rising (see [18] for a review), it is intriguing to consider the rather strong evidence for the explosion being analogous to the case of the K/T boundary. In the former, simple Ediacaran organisms played the role of "dinosaurs", as emphasized by Knoll and Carroll ([18]), then followed by an enormous diversification of the species. Contrary to the K/T case, however, the postulated external trigger (illumination by a GRB) would not leave an obvious signature like the famous iridium layer, and thus subtle evidence should be searched for carefully. In particular, the large and short-lived negative excursion in the carbon-isotopic composition of surface seawater (also present but with a smaller amplitude in the Permo-Triassic extinction) may hold the clue for understanding the likelihood of a large environmental perturbation. An explicit modelling of the dynamics of the populations subject to such a large perturbation (just underway) would shed some light onto this (yet speculative) association.

4 Conclusions

We have shown that a local GRB gamma flux onto the earth should correlate with a massive extinctions of life in the past. We are still exploring the possible role of GRBs as punctuating agents of the biological evolution, and the purpose of this paper has been to show and quantify some of these effects. As discussed in the previous section, we believe that the Cambrian explosion could be a major example of the GRB role. Arguments for extrinsic perturbation associated with an extinction event have been also presented by Benítez, Maíz-Apellaniz and Canelles [22] (a close supernova event) and Melott et al. [23] (a tentative GRB-Ordovician extinction). An earlier version of the present work, focused on the issue of a hypernova-supershell connection has been released as a preprint [24]. It is interesting (but perhaps not significative) to note that some HI supershells (tentatively associated with GRBs as their putative remnants [11], like GSH 139-03-69 should have been almost simultaneous with the Priabonian extinction around 35 Myr ago where cooltemperature-intolerant organisms gradually died, whereas GSH 242-03+37 has a characteristic age of 7.5 Myr where even ^{10}Be marine sediments could be used for testing purposes ([19]). Independently of this, major extinction events older than $\sim 10 Myr$ would not obviously correlate with supershells or other similar structure which should be long dissipated

As stated above, detailed calculations of the response of atmospheres to gamma rays have been recently published [20, 21]. In particular, the model of Ruderman-Schramm-Ellis has been found to provide an overestimate of the ozone destruction. This is just an example of the type of uncertainties one encounters when dealing with this formidable problem. Clearly, much work is needed before we pinpoint and understand the nature and consequences of these events for the ISM and biological activity with confidence.

5 Acknowledgements

We would like to acknowledge E. Reynoso for useful advice on HI observations. We are also grateful to E. M. G. Dal Pino, G. Lugones and G.A Medina Tanco for encouragement and discussions on these subjects. This work has been supported by FAPESP Foundation (São Paulo, Brazil). Steward Observatory colleagues and staff are acknowledged for creating a stimulating working atmosphere during the early realization of this work.

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