

# Biological effects of gamma-ray bursts: distances for severe damage on the biota

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**Abstract:** In this paper we present a unified, quantitative synthesis of analytical and numerical calculations of the effects that could be caused on Earth by a gamma-ray burst (GRB), considering atmospheric and biological implications. The main consequences of the illumination by a GRB are grouped into four distinct classes and analysed separately, namely: direct  $\gamma$  flash, UV flash, O<sub>3</sub> layer depletion and cosmic rays. The effectiveness of each of these classes is compared and distances for significant biological damage are given for each one. We find that the first three effects have the potential to cause global environmental changes and biospheric damage, even if the source is located at galactic distances or even farther afield (up to 150 kpc, where 1 parsec =  $3.09 \times 10^{16}$  m, about five times the Galactic diameter of 30 kpc). Instead, cosmic rays would only be a serious threat for close sources (of the order of a few parsecs).

As a concrete application from a well-recorded event, the effects on the biosphere of an event identical to the giant flare of SGR1806-20 on 27 December 2004 have been calculated. In spite of not belonging to the so-called ‘classical’ GRBs, most of the parameters of this recent flare are quite well known and have been used as a calibration for our study. We find that a giant flare impinging on Earth is not a threat for life in all practical situations, mainly because it is not as energetic, in spite of being much more frequent than GRBs, unless the source happens to be extremely close.

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## Introduction

The implications of astrophysical events on Earth and Earth-like planets are an increasingly active field of research in many distinct areas of knowledge, such as Astronomy, Geology, Meteorology and Biology. Several sources of cosmic catastrophes have been proposed over the years. Recently, gamma-ray bursts (GRBs) were recognized as some of the most energetic astrophysical events since the Big Bang, releasing in just a few seconds as much energy as a supernova, of the order of  $10^{44}$  J but concentrated in hard X-rays and  $\gamma$  radiation. Thorsett (1995) was the first to acknowledge the potential destructive effects of a GRB illuminating the Earth. The question of vital statistics (rates, beaming, etc.) of the bursts is currently being studied, but it is undeniable that damage to the biota could be severe if a burst strikes (or has struck) the planet. Therefore, it is important to understand the various dangerous effects, and in particular their relative importance as a function of the distance for realistic physical inputs, in order to assess the actual threat to living organisms. It is the purpose of this work to present a unified synthesis of numerical and analytical calculations on the atmospheric and biological effects that a GRB might have if

directed towards Earth or to a planet with an Earth-like atmosphere.

It is not unlikely that GRBs (as well as supernovae) have had a great impact on Earth, at least in the last billion years (Melott *et al.* 2004). Their effects range from a direct transmission of the high-energy  $\gamma$  radiation through the atmosphere to chemical alterations on it, such as NO<sub>x</sub> rise and O<sub>3</sub> layer depletion. GRBs may also be associated (Vietri *et al.* 2003) with the acceleration of high-energy cosmic rays, which were taken into account by considering the effects of a massive flux of particles, in the form of a cosmic-ray jet (CRJ), as proposed by Dar *et al.* (1998).

As demonstrated below, our results suggest that ‘classical’ GRBs can have a radius of biological influence as large as 150 kpc. This distance is greater than the galactic radius, and therefore a burst occurring anywhere in the Galaxy could directly affect the biosphere of a planet lying within its beaming cone. It is naively expected that galaxies with strong star formation should be more prone to the occurrence of GRBs, owing to the greater proportion of massive stars, which are considered to be the progenitors of long-duration bursts in most models. Any occurrence of life might have been ‘reset’ by a GRB (Annis 1999), or it may even have

received an evolutionary boost. Irregular galaxies with low metallicity may also be associated with GRBs (Stanek 2006), but these systems are less interesting for astrobiology, because it is still unclear if planets could be formed on them at all.

### Basic assumptions

The model adopted for a long-duration GRB consists of a 'standard'  $\gamma$  energy release of  $5 \times 10^{43}$  J, beamed within a solid angle  $\Delta\Omega \sim 0.01$  sr (Frail *et al.* 2001) and peak duration of approximately 10 s. The emission is generally well-fitted by a broken power law, known as a *Band spectrum*, with its main energy being released in the hundreds of keV range (Band *et al.* 1993), where  $1 \text{ eV} = 1.6 \times 10^{-19}$  J. Absorption by the interstellar medium (ISM) was neglected because the later is almost completely transparent to high-energy photons, and thus the flux at a distance  $D$  should behave as

$$F = \frac{L}{\Delta\Omega D^2}$$

where  $L$  is the  $\gamma$  luminosity and  $\Delta\Omega$  is the beaming solid angle.

Since we shall only be using the observational characteristics of long bursts, we will not take into account the differences of the progenitors which may lead to the event itself, or the different models for explaining the formation of the  $\gamma$  radiation (the Fireball and the Cannonball models being the most popular). The Fireball model associates this kind of burst with very energetic Ic SNe, occasionally dubbed *hypernovae* events (van Paradijs *et al.* 2000). In this model the  $\gamma$  radiation is produced by synchrotron emission during the collision of highly relativistic conical shells ejected during the explosion. In the Cannonball model (Dar & De Rújula 2004), the  $\gamma$  emission is produced by inverse Compton scattering on a bipolar jet made of chunks of ordinary material from a common core-collapsed supernovae, which is ejected when material from an accreting torus falls down on the compact object. In spite of being important for other purposes, these differences do not affect our conclusions, which are insensitive to the specific GRB model.

Some previous works have already made quantitative estimates on individual effects; for example, Thomas *et al.* (2005a,b) made a study of the ozone depletion produced by a GRB using several initial conditions. Since we seek here to build a more complete picture of the problem, we have also considered the effects of transmission of the  $\gamma$  radiation by the atmosphere (Smith *et al.* 2004) and the energy deposited by cosmic rays accelerated within the burst. Thus, for the sake of a clear identification of the different harmful thresholds for the biota related to each effect, we have divided them into four classes:  $\gamma$  flash, UV flash, O<sub>3</sub> layer depletion and CRJs, which will be further discussed and quantified.

After an evaluation of the physical conditions of the photon transfer, two unicellular organisms were used as fiducial biological probes for their effects: the well-known *Escherichia coli* (*E. coli*), an internal, radiation-sensitive (in particular to UV) bacterium, and *Deinococcus radiodurans* (*D. radiodurans*), classified as a polyextremophile owing to its

Table 1. *Doses and fluxes for a 10% survival for the bacteria E. coli and D. radiodurans for ionizing (Ghosal et al. 2005) and UV radiation (Gascón et al. 1995)*

Test organism	$D_{10}^{\text{ion}}$ (kGy)	$F_{10}^{\text{ion}}$ (J m <sup>-2</sup> )	$F_{10}^{\text{UV}}$ (J m <sup>-2</sup> )
<i>E. coli</i>	0.7	$3.50 \times 10^5$	22.6
<i>D. radiodurans</i>	11	$5.50 \times 10^6$	$5.53 \times 10^2$

resistance to many external agents such as UV and ionizing radiation, organic peroxides and desiccation. They represent two extremes of radiation resistance, defining a pragmatic 'surviving zone for life'. We are not claiming that these organisms are representative of the primordial prokaryotic fauna on Earth, but they happen to be useful as biological standards because of the vast amount of available data on their biology. Their radiation resistances are summarized in Table 1 and a discussion on the population dynamics is given in Appendix A.

### Evaluation of $D_{10}$ distances

#### Direct $\gamma$ flash

As discussed in the literature, for example in the recent numerical simulations by Smith *et al.* (2004),  $\gamma$  photons with energies of the order of hundreds of keV lose energy primarily by Compton scattering over the electrons on the atmosphere. During the transmission through the atmosphere, these photons lose energy, with a characteristic energy decrease from around 250 keV to 20 keV.

Following the calculations of Smith *et al.*, a thin atmosphere, such as the one present on the primordial Earth, with  $\rho < 100 \text{ g cm}^{-2}$  would transmit around 1% of the initial  $\gamma$  radiation to the ground, while the present atmosphere (a much thicker one at  $\rho \sim 1024 \text{ g cm}^{-2}$ ) would transmit only around  $10^{-28}$  of the initial  $\gamma$  fluence ( $6 \times 10^{-29}$  J). This means that practically all of the  $\gamma$  energy of the burst would be deposited on a thick atmosphere, while on a thin one a significant fraction of the radiation would still reach the ground, affecting just the illuminated hemisphere owing to the short duration of the burst (typically around 10 s), which is certainly much shorter than the rotation of the Earth.

The main biological effect of  $\gamma$  radiation of this range of energy is free radical production by ionization, which has toxic effects on the cell. The  $D_{10}^{\text{ion}}$  dose for *E. coli* is  $D_{10}^{\text{ion}} = 0.7 \text{ kGy}$  where  $D_{10}^{\text{ion}}$  stands for the necessary dose of ionizing radiation for a 10% survival. For *D. radiodurans*, the  $D_{10}^{\text{ion}}$  is much higher at  $D_{10}^{\text{ion}} = 11 \text{ kGy}$ . These doses can be converted to fluxes by using the energy losses on water. For *E. coli*, we have  $F_{10}^{\text{ion}} = 3.5 \times 10^5 \text{ J m}^{-2}$  and for *D. radiodurans*  $F_{10}^{\text{ion}} = 5.5 \times 10^6 \text{ J m}^{-2}$  of  $\gamma$  flux. In order to obtain such fluxes on the surface of the planet, we have to consider the transparency of the atmosphere to the  $\gamma$  radiation, as stated above.

For *E. coli* with a thin atmosphere, the maximum distance at which the  $\gamma$  flash would deliver a  $D_{10}^{\text{ion}}$  dose at the surface of the planet was calculated to be 390 pc, and for *D. radiodurans* the corresponding figure was 100 pc. As previously stated, for the thick atmosphere this mechanism would be very

inefficient as the  $\gamma$  radiation would be deposited on the atmosphere itself.

*UV flash*

The same Compton mechanism blocking the direct irradiation provokes a large fraction of the high-energy  $\gamma$  photons to have its energy lowered to the UV range.

Smith *et al.* (2004) calculated that, for a thin atmosphere, 1–10% of the initial  $\gamma$  flux would be converted to UV flux, while for a thick atmosphere the fraction is in the range  $2 \times 10^{-3}$ – $40 \times 10^{-3}$ . We observe that these calculations were performed without considering the presence of aerosols or clouds, which could quite effectively block the UV radiation. As this effect would last for just a few seconds, this means that the instantaneous condition of the atmosphere might substantially change the amount of radiation arriving on the ground.

The biological effectiveness of the UV radiation as a harmful factor comes from the fact that DNA and RNA strongly absorb in this range of energy, suffering mainly from nucleotide dimerization, especially on the pyrimidines (Häder & Sinha 2005). In fact, the UV flux necessary to deposit a  $D_{10}^{UV}$  dose on *E. coli* is  $F_{10}^{UV} = 22.6 \text{ J m}^{-2}$  (Gascón *et al.* 1995), a value  $10^4$  times lower than from ionizing radiation. Again, for *D. radiodurans*, this value is higher,  $F_{10}^{UV} = 5.53 \times 10^2 \text{ J m}^{-2}$  (Ghosal *et al.* 2005). These fluxes can be also translated into distances. Using the same procedure as before and considering the  $\gamma$  to UV conversion efficiencies given by Smith *et al.* (2004), the  $\gamma$  flux on the top of the atmosphere to deliver a  $D_{10}^{UV}$  dose on the ground should be 10–100 times greater than the  $F_{10}^{UV}$  of each organism, which implies maximum distances of 48–152 kpc for *E. coli* and 10–31 kpc for *D. radiodurans*, both for thin atmospheres. For the thick atmosphere case, the range is 21–96 kpc for *E. coli* and 4–9 kpc for *D. radiodurans*. These distance ranges arise from the uncertainty on the  $\gamma$  to UV conversion, as presented above.

*O<sub>3</sub> layer depletion*

The  $\gamma$  radiation may alter the chemistry of the atmosphere, the most relevant change to our study being a rise in the concentration of  $\text{NO}_x$ , which can act as a catalyser for  $\text{O}_3$  degradation. This problem has already been addressed by Ruderman (1979) in relation to the effects of SN explosions on the atmosphere.

Ruderman’s calculations are based on the catalytic destruction of  $\text{O}_3$  by  $\text{NO}$ :



The kinematics of the reaction was modelled in a simplified manner by the equation

$$\frac{[\text{O}_3]}{[\text{O}_3]_0} = \frac{\sqrt{19 + 9X^2} - 3X}{2}, \tag{2}$$

$$X = \frac{[\text{NO}_x]}{[\text{NO}_x]_0}. \tag{3}$$

Ruderman’s work included the following assumptions:

- the oxidation of  $\text{NO}_2$  by  $\text{O}$  is the limiting step of the cycle;
- the  $[\text{O}]/[\text{O}_3]$  ratio is taken to be constant.

During the  $\gamma$  irradiation, the  $[\text{NO}_x]$  rises owing to the production of free N atoms



If we consider all the  $\text{NO}_x$  to be  $\text{NO}$ , the production rate is given by

$$\frac{10}{(10+y)} = \frac{\text{NO molecules}}{\text{ion pair}} \tag{5}$$

where  $y$  is the initial concentration in parts per billion (ppb), which will be taken to be 3 ppb.

Using Ruderman’s figures (Ruderman 1979), we have that 1 J of  $\gamma$  radiation produces  $2.8 \times 10^{17}$  ion pairs. The rate of production of  $\text{NO}$  molecules is then

$$\begin{aligned} R_{\text{NO}} &= \phi \times 2.8 \times 10^{17} \left( \frac{\text{ion pairs}}{\text{J}} \right) \\ &\times \left( \frac{10}{10+y} \right) \left( \frac{\text{NO molecules}}{\text{ion pairs}} \right) \times \frac{10^9}{5 \times 10^{27}} \end{aligned} \tag{6}$$

where  $\phi$  is in units of  $(\text{J m}^{-2}) \text{ s}^{-1}$ . Simplifying and integrating over the duration of the burst yields (in ppb)

$$R_{\text{NO}} = 0.43\phi \tag{7}$$

where  $\phi$  is in units of  $\text{J m}^{-2}$ . Using the definition (3) with  $[\text{NO}]_0 = 3 \text{ ppb}$ , we finally obtain

$$X = \frac{[\text{NO}]}{[\text{NO}]_0} = 1 + \frac{R_{\text{NO}}}{[\text{NO}]_0}, \tag{8}$$

$$X(\phi) = 1 + 0.67 \times 10^{-2} \phi. \tag{9}$$

where  $\phi$  is in units of  $\text{J m}^{-2}$ . The  $\text{NO}$  thus produced has a dynamical time of residence in the atmosphere of the order of 2–6 yr (Ruderman 1979). Using Eq. (2), we may obtain the ozone depletion as a function of the  $\gamma$  fluence on the top of the atmosphere, as presented in Fig. 1. Ellis & Schramm (1995) later considered the same problem, with the addition of the effect of charged particles produced by the SN event, considering its ionizing power to be the same as the electromagnetic component. Their results are even more dramatic and may be adapted immediately for a GRB.

Recently, Gehrels *et al.* (2003) produced a more sophisticated treatment for the problem, using a 2D atmospheric simulation code developed at the Goddard Space Flight Center, and using an input spectrum from SN1987a, with a total energy release of  $9 \times 10^{39} \text{ J}$ . Running the simulation at 10, 20, 50 and 100 pc, their results suggest a tendency for ozone depletion to scale as  $D_{5N}^n$ , where  $1.3 < n < 1.9$ . In our calculations we used a mean value of  $n = 1.6$ .

We calculated the mean ozone depletion at 10 pc using the latest results from Gehrels *et al.* (2003) to be 22.6%, and from this value we scaled to the effects of interest, obtaining the depletion of  $\text{O}_3$  (see Fig. 1):

$$\frac{[\text{O}_3]}{[\text{O}_3]_0} = 1 - 7.2 \times 10^{-4.6} \phi^{0.8} \tag{10}$$

where  $\phi$  is in units of  $\text{J m}^{-2}$ .

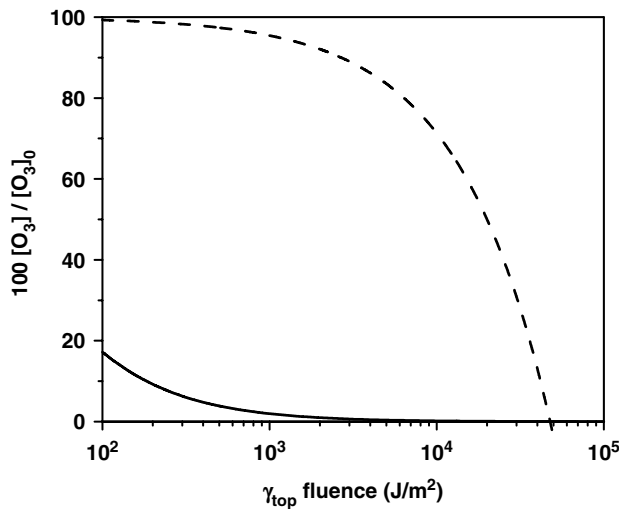


Fig. 1. Atmospheric ozone depletion as a function of the initial  $\gamma$  fluence, as calculated by Ruderman (1979) (solid line), using an analytical simplified approach, and by Gehrels *et al.* (2003) (dashed line) using numerical simulations.

Comparing Ruderman’s results with those of Gehrels *et al.*, we appreciate the large differences between both approximations. Ruderman’s results indicate that with fluences of  $10^3 \text{ J m}^{-2}$  essentially all the  $\text{O}_3$  would be destroyed, while the recent simulations show that a modest fraction remains. This is caused by the strong simplifications adopted in Ruderman’s work, in particular the simplifications to the chemical reactions and the fact that atmospheric mixing is neglected, so that the problem could be solved analytically (Crutzen & Brühl 1996). We have thus adopted the milder scenario presented by Gehrels *et al.* (2003). In particular, Thomas *et al.* (2005a, b) repeated the calculations using the same code but with an input spectrum of a GRB, which has a much shorter time scale than SNe. However, their results did not change our conclusions significantly.

To calculate the increase of the solar UV caused by the depletion of the  $\text{O}_3$  layer, we used a Beer–Lambert law

$$\phi_{\text{UV}} = (\phi_{\text{UV}})_0 e^{-\sigma N} \tag{11}$$

where  $\sigma$  is the  $\text{O}_3$  cross-section and  $N$  is the column density of  $\text{O}_3$ . In this approximation we ignore other UV absorbers, such as water vapour and scattering particles, which are not expected to dominate. The initial mean value for the column density of  $\text{O}_3$  used was 350 DU, or equivalently  $9.4 \times 10^{22} \text{ molecules m}^{-2}$ .

We may now introduce the depletion factor from Eq. (10) into Eq. (11), and thus obtain the solar  $\text{UV}_B$  flux on the ground already increased by the depletion of the  $\text{O}_3$  layer as a result of the  $\gamma$  flux from the GRB:

$$\phi_{\text{sup}} = \phi_0 \exp \left[ - \left( \sigma \frac{[\text{O}_3]}{[\text{O}_3]_0} N \right) \right] \tag{12}$$

where  $\phi_{\text{sup}}$  is in units of  $(\text{J m}^{-2}) \text{ s}^{-1}$ . The results are depicted in Fig. 2. The  $D_{10}^{\text{UV}}$  distance for *D. radiodurans* is 12 kpc, or essentially the Galactic radius. Closer bursts increase

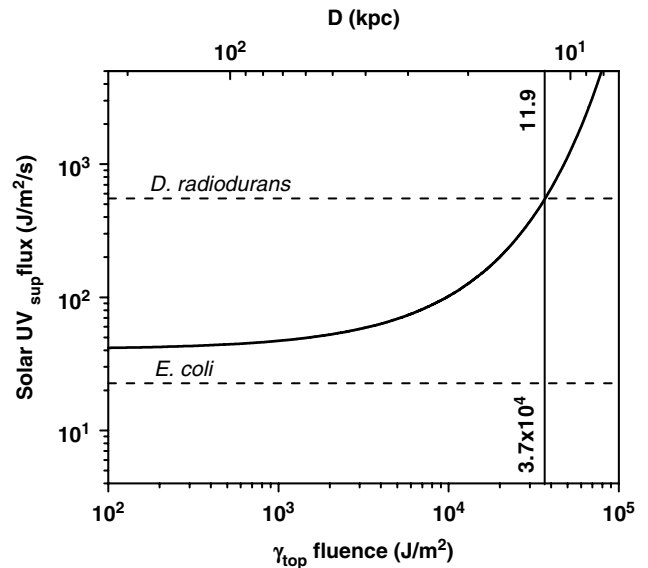


Fig. 2. Calculated solar UV flux reaching sea level, attenuated by the depleted ozone layer, as a function of the initial  $\gamma_{\text{top}}$  fluence (lower scale) and distance to the standard GRB (upper scale). The  $F_{10}^{\text{UV}}$  for *E. coli* and *D. radiodurans* are also plotted.

dramatically the mortality for almost all types of exposed unicellular organisms. The *E. coli*  $F_{10}^{\text{UV}}$  is below the actual solar UV flux on the ground, even without ozone depletion, which is consistent with *E. coli* being an internal micro-organism and does not result in a useful limit.

#### Cosmic-ray jets

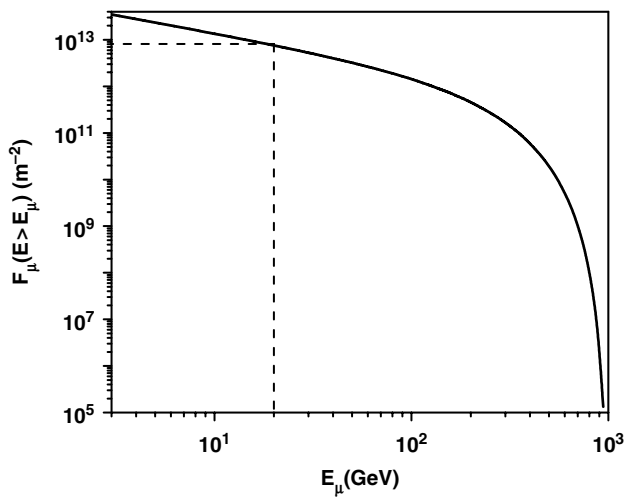
This is the last effect to be considered in our work. Being an explosive phenomenon, Dar *et al.* (1998) proposed that a GRB may be associated with a massive acceleration of cosmic rays, which could be beamed into a jet and reach great distances from the source, called the *cosmic-ray jet* (CRJ). Although still very speculative, it is worth taking a serious look into this hypothesis and in particular to the consequences regarding to planet illumination by the GRB, since it could also be struck by the jet, but with a substantial time delay.

It is generally assumed in the calculations that the same amount of energy seen in  $\gamma$  radiation is used to accelerate the particles (termed the equipartition hypothesis; see, e.g., Vietri *et al.* (2003)), which we shall consider to be protons. This way, we considered a jet of protons with  $5 \times 10^{43} \text{ J}$  of kinetic energy and assume the same collimation angle inferred for the photons,  $\Delta\Omega = 1/\Gamma$ , with  $\Gamma \approx 100$ .

Hitting the upper atmosphere, the CRJ would produce a shower of secondary particles. We have focused our attention on the muons, which could arrive on the ground and even underground or deep underwater, unlike UV or  $\gamma$  radiation which is restricted to the surface. In fact this is one of the main arguments given by Dar *et al.* (1998) for why CRJs could potentially have a major impact on life.

The production of muons in the atmosphere occurs when a proton interacts with a nucleus in the following sequence:





**Fig. 3.** Muon flux on sea level produced by the interactions of 1 TeV protons on top of the atmosphere, not considering muon decay. For muons over 20 GeV, the expected muon flux is of the order of  $10^{13} \text{ m}^{-2}$ .

In the case of a monochromatic primary flux, we can use the simplified formula (Dar *et al.* 1998)

$$\langle N_\mu \rangle \cong \frac{(0.0145E_p)}{\cos \theta} (E_p/E_\mu)^{0.757} (1 - (E_\mu/E_p))^{5.25} \quad (14)$$

where  $E_p$  is in units of TeV. This gives the mean number of high-energy muons ( $E > E_\mu$ ) produced by nucleons of energy  $E_p$ , which do not decay in the atmosphere and reach the sea level with zenithal angle  $\theta < \pi/2$ .

To introduce the incident spectrum of the primaries, we can use the equation given by Lipari (1993), deducible using standard physics (e.g. Gaisser 1992):

$$\begin{aligned} \phi_\mu(E, \theta) = & \left[ L_\pi(\alpha) \left( 1 + \frac{L_\pi(\alpha)}{H_\pi(\alpha)} \frac{E \cos \theta}{\epsilon_\pi} \right)^{-1} + L_K(\alpha) \right. \\ & \left. \times \left( 1 + \frac{L_K(\alpha)}{H_K(\alpha)} \frac{E \cos \theta}{\epsilon_K} \right)^{-1} \right] KE^{-\alpha}. \end{aligned} \quad (15)$$

These formulae are strictly valid for muon energies greater than 20 GeV, because muon decay processes are not taken into account. The input spectrum is characterized by the index square and the constant  $K$  (these parameters were taken from the work of Lipari (1993)). This formula was tested successfully using the usual cosmic-ray background ( $\alpha = 2.7$  and  $K = 1.85$ ) reproducing the actual flux, except at low energies where the Solar wind and other effects are important.

The main process of energy loss for high-energy muons on matter is ionization. To calculate the ionization losses, we used a simplified well-known version of the Bethe–Bloch equation (Richard-Serre 1971), which is valid strictly for energies above 10 GeV:

$$\begin{aligned} \left( \frac{dE}{dx} \right)_{\text{ioniz}} = & \frac{Z}{A} \left[ 4.55 + 2.34 \times 10^{-4} \eta - 2.62 \right. \\ & \left. \times 10^{-8} \eta^2 - 0.1535 \ln \left( \rho \frac{Z}{A} \right) \right], \end{aligned} \quad (16)$$

Table 2.  $D_{10}$  distances for the various effects following a GRB, clearly showing the longer range for the UV Flash mechanism. The quoted ranges for the UV Flash reflect the uncertainty in the fraction of  $\gamma$  to UV conversion efficiency (see text). Nor the ozone depletion nor the CRJ effects is relevant on the thin atmosphere case, and for *E. coli*, the  $D_{10}$  distance is not calculated for ozone depletion because it is already below the  $D_{10}$  threshold without the burst

Planetary effect	Test organism	$D_{10}$ distance (kpc = $3 \times 10^{19}$ m)	
		Thin atmosphere	Thick atmosphere
$\gamma$ flash	<i>E. coli</i>	0.39	Negligible
	<i>D. radiodurans</i>	0.10	Negligible
UV flash	<i>E. coli</i>	48–152	21–96
	<i>D. radiodurans</i>	10–31	4–19
O <sub>3</sub> layer depletion	<i>E. coli</i>	–	–
	<i>D. radiodurans</i>	–	12
CRJ	<i>E. coli</i>	–	0.05
	<i>D. radiodurans</i>	–	0.01

$$\eta = \beta\gamma = \left[ \left( \frac{E}{M_\mu c^2} - 1 \right) \frac{E}{M_\mu c^2} \right]^{1/2}$$

In water, Eq. (16) gives an approximate constant energy loss of  $2.58 \text{ (MeV g}^{-1}\text{ cm}^{-2})$ , for muon energies up to 1 TeV.

In the absence of a firm evaluation of the spectrum, we have decided not to employ any specific one for the particles accelerated at the GRB, but rather a monochromatic flux of typical energy per nucleon of 1 TeV. The duration of the irradiation by these relativistic particles is estimated to be  $\approx 2$  months (Dar *et al.* 1998).

For a primary energy flux of  $10^4 \text{ J m}^{-2} \cong 10^{12} \text{ TeV m}^{-2}$  in high-energy particles, which is the assumption for our standard burst at 10 kpc, we have calculated the muon flux at sea level, as shown in Fig. 3.

The lethal dose of ionizing radiation for humans is around 3 Gy, which can be translated to a muon flux, at the 20 GeV energy range, of about  $10^{14} \text{ m}^{-2}$ . Our benchmark organisms *E. coli* and *D. radiodurans* are much more resistant, the  $D_{10}^{\text{ion}}$  dose being 0.7 kGy for *E. coli* and 11 kGy for *D. radiodurans*. Consequently, these bacteria could stand higher muon fluxes,  $2 \times 10^{16} \text{ m}^{-2}$  for *E. coli* and  $3 \times 10^{17} \text{ m}^{-2}$  for *D. radiodurans*. These numbers set  $D_{10}^{\text{ion}}$  distances for the burst source of 300 pc for humans, 48 pc for *E. coli* and 12 pc for *D. radiodurans*.

### Discussion and conclusions

As a summary of the above results, we present in Table 2 the  $D_{10}$  distances for *E. coli* and *D. radiodurans* calculated for the various mechanisms presented.

We can safely state that the most efficient damaging effect of GRB illumination is the UV flash, because it can deliver a  $D_{10}$  dose for distances up to 150 kpc. However, this effect is limited to one hemisphere, and only over uncovered land and shallow waters. It may not have a direct global impact, although it may have an indirect long-term effect if a significant part of the planktonic organisms are killed during the irradiation. The non-linear effects on populations of a huge catastrophe such as the incidence of a nearby GRB are difficult to model and there is ample room to study scenarios addressing these issues.

The direct  $\gamma$  flash seems not to be biologically important, because most of its energy would be absorbed by the atmosphere. For a thick atmosphere, the energy deposition would probably lead to an increase in temperature of a few degrees, but for a thin one the results could be even more dramatic. However, the climatic consequences of these are not totally clear and it would be interesting to model such a large disturbance in some detail.

The depletion of the ozone layer is the most obvious global and long-term effect. It can affect life for many years, probably making the surface of the planet an environment uninhabitable for its photosynthesizing biota. It can be effective for distances up to 12 kpc for *D. radiodurans*, which means almost anywhere in the Galaxy, even for a radiation resistant organism, confirming the expectations of Thorsett (1995). In fact, it is difficult to imagine a fundamental ecosystem dependent on photosynthetic organisms not to be at least harmed by the occurrence of a directed GRB event closer than a few kpc. UV radiation has been proposed to have a role in extinctions on Earth (Cockell 1999), and it is important to consider GRBs as additional sources of ozone depletion.

Other consequences are expected as well, as pointed out by Thorsett (1995) and by Thomas *et al.* (2005b): the rise of the  $\text{NO}_x$  concentration in the atmosphere may have a global cooling effect, blocking visible sunlight and making photosynthesis inefficient. On the other hand, the residual nitrates of this process may make the soil more fertile after the end of this GRB winter, allowing lands to be populated by vegetation (see Thomas *et al.* (2005b)).

The cosmic-ray effect is still controversial, and it seems to be very inefficient unless the source is located in close proximity (of the order of a few pc) to the Earth. However, a non-lethal CRJ incidence could still be important for the biota, for example by providing a higher level of background radiation which could induce significant mutation rates. As its effect lasts for several months, these mutations might have time to accumulate on simple, fast replicating organisms, having a yet unknown evolutionary importance (Dermer & Holmes 2005).

We conclude our unified study of the several effects of GRBs with a quantitative assessment of how destructive an event could be, leading to extermination of life or at least part of it. However, it is not impossible that it may work as an evolutionary kick inducer, in common with many

Table 3.  $D_{10}$  distances for the various effects following a SGR. The quoted ranges reflect the uncertainty on the distance to the source and on the fraction of  $\gamma$  to UV conversion efficiency (see text). Nor the ozone depletion nor the CRJ effects is relevant on the thin atmosphere case, and for *E. coli*, the  $D_{10}$  distance is not calculated for ozone depletion because the solar flux on the ground is already above the  $D_{10}$  threshold without ozone loss

Planetary effect	Test organism	$D_{10}$ distance (pc = $3.1 \times 10^{16}$ m)	
		Thin atmosphere	Thick atmosphere
$\gamma$ flash	<i>E. coli</i>	0.06–0.09	Negligible
	<i>D. radiodurans</i>	0.01–0.02	Negligible
UV flash	<i>E. coli</i>	7–35	3–22
	<i>D. radiodurans</i>	1–7	1–4
$\text{O}_3$ layer depletion	<i>E. coli</i>	–	–
	<i>D. radiodurans</i>	–	2–3
CRJ	<i>E. coli</i>	–	0.01
	<i>D. radiodurans</i>	–	Negligible

other apparent catastrophic events that happened on Earth (Horvath 2003).

#### Case study: SGR1806-20

On 27 December 2004, a giant flare event from the soft gamma repeater SGR1806-20 was observed. The main characteristics of this event were as follows:

- peak flux:  $F_{\text{peak}} > 0.3 \times 10^{-3} \text{ J m}^{-2}$  (Nakar *et al.* 2005);
- estimated distance:  $6.4 \text{ kpc} < D < 9.8 \text{ kpc}$  (Cameron *et al.* 2005);
- beaming angle:  $\Delta\Omega \sim 0.03 \text{ sr}$  (Yamazaki *et al.* 2005);
- $\gamma$  isotropic luminosity:  $1.5 \times 10^{38} \text{ J} < L < 3.5 \times 10^{38} \text{ J}$
- $\gamma$  luminosity with beaming:  $3.5 \times 10^{36} \text{ J} < L < 0.8 \times 10^{37} \text{ J}$

This kind of event is thought to share many of its characteristics with classical GRBs, but scaled to lower energies (Nakar *et al.* 2005). Although different in origin they are of interest because there are another three currently known SGRs in the Galaxy, so that they are not of cosmological origin and might have more direct implications to life, even at present.

By applying the same method as previously used for the GRBs, we arrived at the  $D_{10}$  distances for the effects studied. The results are summarized in Table 3. As in the case of GRBs, we found that the most effective mechanism is UV flash because it corresponds to the largest calculated  $D_{10}$  distance. However, this type of event needs to occur very close to Earth to lead to any dramatic consequences, so close that in fact we do not expect to have had any progenitors in the history of the planet.

For the case of a CRJ, we do not expect to have any direct biological effect at all given the spreading of the particles by magnetic fields (Biermann *et al.* 2004) as, although the acceleration of high-energy particles by internal shocks in the SGR1806-20 is a possibility (as discussed by Asano *et al.* (2005)), it is not relevant for our purposes.

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## Appendix A. Population dynamics

The use of the  $D_{10}$  doses throughout this work is a way of employing a common standard for population damage; by no means should it be considered a general lethal or critical ecological threshold. For that, more complex population dynamics should be taken into account.

One approach to understanding what can be considered a significant population depletion, where by significant we mean that the population is at risk of extinction, is to define the concept of the minimum viable population (MVP). This concept was first introduced by Shaffer (1981), considering the ecological and economical problems of keeping natural reserves as small as possible and still retaining biodiversity. Therefore, it is a concept usually adopted for macroscopic populations. As Shaffer stated:

‘A minimum viable population for any given species in any given habitat is the smallest isolated population having a 99% chance of remaining extant for 1000 years despite the foreseeable effects of demographic, environmental, and genetic stochasticity, and natural catastrophes.’

Shaffer considered it an *ad hoc* definition, because there is no special reason for the choices of 99% and 1000 yr. He makes clear the necessity of adapting this definition to the system of interest.

The concept seems valid for a variety of systems: if a population becomes too small, it may become extinct. The problem is how to assess such a number, which is strongly dependent on the system and its interactions with its surroundings. Shaffer proposes five ways of doing so.

- *Experiments.* The viability of doing experiments depends on the system, because it is necessary to find or create isolated populations and follow their persistence for a time scale relevant to that species.
- *Biogeographic patterns.* The observations of distribution patterns that occur on islands or fragmented regions can give a first insight into the minimum areas required for the populations and, by estimating the densities, one can calculate the MVP. This approach requires the species already to be in equilibrium on the isolated regions, and that the time of isolation is known (by geological clues, for instance). However, the estimates may not be promptly extrapolated because the interspecies and environmental interactions can be very distinct.
- *Theoretical models.* There are many theoretical models which can predict the probability of survival of a small population but these normally are not based on realistic

biological hypothesis, being over-simplified, or they get into unsolved mathematical problems. The diffusion theory, as applied by many authors, can be used on totally unpredictable environments.

- *Numerical simulations.* By not suffering the limitations of the purely theoretical models, these can be the most useful way to calculate the MVP. They can be more realistic and accept many more parameters from the actual biological system, allowing their prompt modification, as well as their interdependencies. However, the simulations are extremely specific to the system being modelled, failing to give general conclusions. They also need accurate knowledge of the critical parameters to assure a realistic simulation.
- *Genetic considerations.* Many authors follow genetic and evolutionary arguments to recommend MVP. Franklin (1980) suggests that, to keep short-term fitness, the effective size of the population has to be greater than 50 individuals. He also proposes that, for an environment in alteration, in order to assure sufficient genetic variability for adaptation, the number must be around 500. These recommendations are based on generalized applications of basic genetic principles, and thus they may suffer from over-simplifications.

Following the tendency to concentrate MVP calculations for macroscopic species endangered by extinction, a great deal of models take into account the so-called Allee effect, i.e. the sensitivity of a population to a low density of individuals owing to the difficulty in finding mating partners. Microorganisms, in contrast with sexually reproducing ones, are not subjected to the Allee effect. However, horizontal gene transfer (HGT) seems to be an essential mechanism on the prokaryotic domain of life (Allers & Mervarech 2005), which may imply an analogue of the Allee effect to guarantee genetic variability. It is clear that understanding the full importance of HGT is fundamental to comprehending the evolutionary processes during the unicellular era of the Earth. We must emphasize that, by neglecting the HGT, models that intend to predict the MVP for unicellular organisms may be underestimating it. As some authors suggest that up to 30% of the prokaryotic genetic material may be of HGT origin (Allers & Mervarech 2005) we must consider that the difference between a purely vertical gene transfer (VGT) model and a VGT/HGT hybrid model should be significant on the MVP calculation. These values are not yet present in the literature.

Similarly to Franklin (1980), other authors (Soulé 1986; Nunney & Campbell 1993) have arrived at a MVP of 10 for microorganisms. Chiba (1998) makes a systematic analytical study of the problems of calculating the MVP in a general way, using as an example an exponentially growing population, which is a good model for microorganisms, but also neglecting HGT. In a similar approach, McCarthy (2001) calculates the MVP using stochastic methods and Monte Carlo simulations, arriving at the important result that, although populations may float abruptly with the variation of the model parameters (as perturbations), as long as the MVP is not reached, extinction should not take place. He also demonstrated that the MVP changed gradually, not abruptly,

with parameter variations. This result validates the concept of MVP for extinction models.

As an experimental test for the theoretical MVP for microorganisms, Quang (1998) showed that the smallest viable population of a few species of aquatic bacteria, during the period of the experiment, fluctuated around 10 cells ml<sup>-1</sup>.

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