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TERRESTRIAL OZONE DEPLETION DUE TO A MILKY WAY GAMMA-RAY BURST

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ABSTRACT

Based on cosmological rates, it is probable that at least once in the last gigayear the Earth has been irradiated by a gamma-ray burst (GRB) in our Galaxy from within 2 kpc. We have performed the first detailed computation of the effects on the Earth's atmosphere of one such impulsive event: A 10 s 100 kJ m^{-2} burst penetrates to the stratosphere causing globally averaged ozone depletion of 35%, with depletion reaching 55% at some latitudes. Significant depletion persists for over 5 years after the burst. A 50% decrease in ozone column density leads to approximately 3 times the normal UVB (280–315 nm; a wavelength band that ozone significantly absorbs and that living organisms are sensitive to) flux, and widespread extinctions are likely, based on extrapolation from sensitivity of modern organisms. Additional effects include a shot of nitrate fertilizer and NO_2 opacity in the visible, providing a cooling perturbation to the climate over a similar timescale. These results lend support to the hypothesis that a GRB may have initiated the late Ordovician mass extinction (Melott et al.).

Subject headings: astrobiology — gamma rays: bursts

Online material: color figures, mpeg animation

1. INTRODUCTION

Gamma-ray bursts (GRBs) within our Galaxy have been suggested as a possible threat to life on Earth (Thorsett 1995; Scalo & Wheeler 2002; Dar & De Rujula 2002; Melott et al. 2004). Some effects similar to those due to a nearby supernova (SN; Gehrels et al. 2003) are expected. GRBs are rarer than supernovae, but their greater energy output results in a larger region of influence, and hence they may pose a greater threat. It is likely (Melott et al. 2004; Dermer & Holmes 2005) that in the last gigayear, a GRB has occurred close enough to have had dramatic effects on the stratospheric ozone, leading to detrimental effects on life through increases in solar ultraviolet (UV) radiation, which is strongly absorbed by ozone. A major question has been the timescale for atmospheric chemistry: most of the GRB fluence comes in seconds or minutes versus months for supernovae.

In order to gain a more detailed and accurate insight into these expected effects, we have performed computations using the Goddard Space Flight Center (GSFC) two-dimensional atmospheric model. This model has been used previously to investigate the atmospheric effects of SNe (Gehrels et al. 2003). The computations discussed here are significantly more challenging because of the extremely short duration and greater energy output of GRBs in comparison to SNe.

2. METHODS

We take as "typical" a GRB with power 5×10^{44} W (isotropic-equivalent) and duration 10 s, whose gamma-ray spectrum is described by the Band spectrum (Band et al. 1993). These assumptions are drawn from observations and are not dependent on beaming angle. We have determined the depletion of ozone for such a GRB beamed at the Earth from a distance of 2 kpc, delivering to the Earth a total fluence of 100 kJ m^{-2}. This distance corresponds to that of a probable nearest "typical" GRB in the last gigayear, based on conservative assumptions (Melott et al. 2004).

The prompt effect of this burst at the Earth's surface is a "flash" of UVB (280–315 nm; a wavelength band that ozone significantly absorbs and that living organisms are sensitive to) radiation with power ~20 W m^{-2} (Smith et al. 2004). This is about 7 times the intensity at the Earth's surface on a bright, sunny day, but it is brief and so is not likely to have a major effect. Longer term effects explored here include ozone depletion and the resulting increase in solar UVB flux. We have not included the effects of any ultra–high-energy (>10^{18} eV) cosmic rays from a GRB (Dermer & Atoyan 2004; Waxman 2004a, 2004b; Dermer & Holmes 2005) because of the uncertainty as to whether and at what energies GRBs may produce such particles.

The GSFC two-dimensional model is described in Douglass et al. (1989), Jackman et al. (1990), and Considine et al. (1994). The model's two dimensions are latitude and altitude (ranging up to about 116 km). The latitude range is divided into 18 equal bands and extends from pole to pole. The altitude range includes 58 evenly spaced logarithmic pressure levels (approximately 2 km spacing). A lookup table is used for the computation of the photolytic source term, used in calculations of photodissociation rates of atmospheric constituents by sunlight (Jackman et al. 1996). Winds and small-scale mixing are included as described in Fleming et al. (1999). For this study, we have removed anthropogenic compounds such as chlorofluorocarbons.

We have employed two versions of the model. One is intended for long-term runs (many years) and includes all transport mechanisms (e.g., winds and diffusion); it has a time step of 1 day and computes daily averaged constituent values. The second is used for short-term runs (a few days) and calculates constituent values throughout the day and night, but does not include transport. Previously, this version has been used with a time step of 225 s (Jackman et al. 2001). In the current study,

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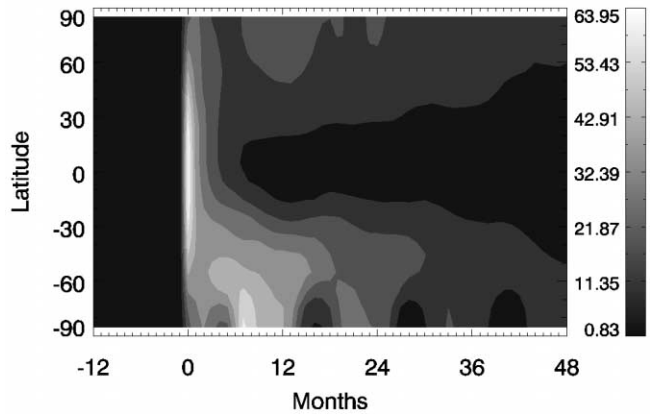

FIG. 1.—Column density of NO_y in units of 10^{18} cm^{-2} (the burst occurs at month 0). [*See the electronic edition of the Journal for a color version of this figure.*]

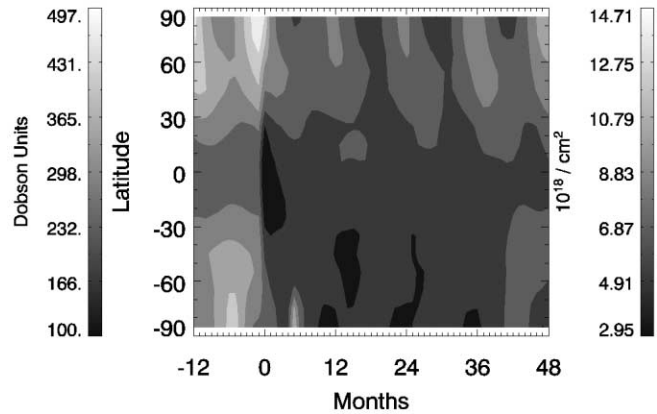

FIG. 2.—Column density of O_3 with scales for both Dobson units (*left*) and 10^{18} cm^{-2} (*right*). The burst occurs at month 0. [*See the electronic edition of the Journal for a color version of this figure.*]

we have used a time step of 1 s in order to allow for spreading our GRB gamma radiation input over several time steps.

Gamma rays are introduced in the model in a manner similar to Gehrels et al. (2003), who used the spectrum of SN 1987A. We use the gamma-ray differential photon count spectrum of Band et al. (1993), which consists of two smoothly connected power laws. We use the following typical values for the break energy and power-law indices, respectively: $E_0 = 187.5$ keV, $\alpha = -0.8$, $\beta = -2.3$ (Preece et al. 2000). The total incident energy is scaled to our desired value (in this study, corresponding to a fluence of 100 kJ m^{-2}). The total photon flux in each of the 66 evenly spaced logarithmic energy bins, ranging $0.001 \leqq E \leqq 10$ MeV, is obtained by integrating the Band spectrum for each bin.

All simulation runs used for analysis were begun with initial conditions obtained from a long-term (roughly 40 years) run intended to bring the model to equilibrium. Constituent values from this run are read in by the 1 s time step version of the model that runs for 7 days (beginning at noon), either with or without input of gamma rays. Runs including gamma radiation treat the burst as a step function at noon on day 4, with a duration of 10 s. In the current study, the burst is input in late March (near the spring equinox) over the equator. (Forthcoming studies will investigate the effects of varying intensity, incidence angle, and times of year at which the burst occurs.) Constituent values from this type of run are then read in by the 1 day time step version that is run for 20 years in order to investigate long-term effects and to determine how the atmosphere returns to equilibrium, preburst conditions. Ozone depletion is computed by comparing such a combined base-short-long run without gamma-ray input to such a run with the burst included.

3. RESULTS

Stratospheric ozone is lost through several catalytic reactions involving oxygen-, nitrogen-, hydrogen-, chlorine-, and bromine-containing gases. The constituents in the stratosphere are generally grouped into "families" such as O_x [O3, O, O(^{1}D)], NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, $ClONO_2$, $BrONO_2$), HO_x (H, OH, HO_2), Cl_y (chlorine-containing inorganic molecules), and Br_y (bromine-containing inorganic molecules), which allow for efficient computation of the chemistry and transport effects. We assume that there were no anthropogenic sources for any of these families, as human influence has been negligible for most of geologic time.

In the case of a large input of gamma rays to the atmosphere, NO_y compounds (most importantly NO and NO_2) are created through the dissociation of N_2 in the stratosphere, which then reacts quickly with O_2 to generate NO. Subsequent reactions create NO_2 and other compounds. Together, these react catalytically to deplete O_3 through the cycle $NO + O_3 \rightarrow NO_2 + O_2$, $NO_2 + O \rightarrow NO + O_2$. The net result is $O_3 + O \rightarrow O_2 + O_2$.

Other reactions can complicate this cycle, such as the destruction of NO by the reaction with N; the production of O_3 through reactions of NO with HO_2; and the interference of NO_y with other families (chlorine-, bromine-, and hydrogen-containing constituents) that reduces the ozone depletion from these families. Some uncertainties in the atmospheric model's treatment of this cycle are discussed in § 4.

The primary results of our simulations are increases in NO_y and decreases in O_3. Ozone column densities can then be used to calculate the resulting UVB flux at the Earth's surface. UVB is particularly dangerous to organisms because DNA is damaged by absorption in this wavelength range.

Results of our modeling are shown in Figures 1, 2, and 3. We have modeled the effects of 100 kJ m^{-2} total incident gamma-ray fluence, input as described in § 2. This corresponds to our "typical" GRB located at about 2 kpc. Fig-

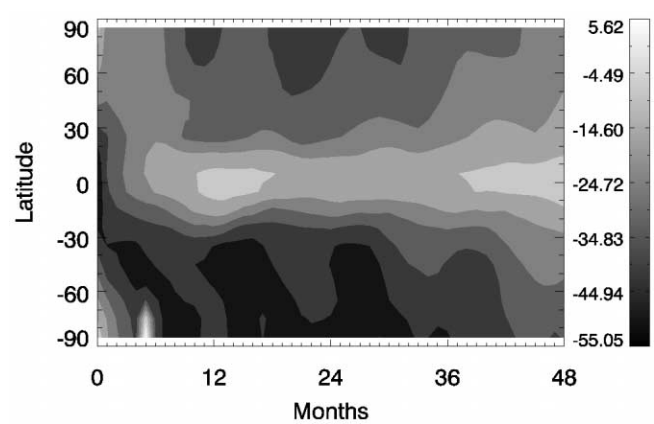

FIG. 3.—Pointwise percent change in column density of ozone (comparing runs with and without burst). [*See the electronic edition of the Journal for a color version of this figure.*]

ure 1 shows the vertical column density of NO_y at each latitude over time. The burst is input at time 0. Figure 2 shows the vertical column density of O_3. Included are scales in both Dobson units (the usual unit of ozone column density) and 10^{18} cm^{-2}. A Dobson unit describes the thickness of a column of ozone at standard temperature and pressure and is defined as 1 DU = 0.01 mm thickness (or 1 DU = 2.69×10^{18} cm^{-2}). Figure 3 shows the percent difference at a given location (between a run with gamma-ray input and one without) in vertical column density of O_3. Immediate depletion of ozone is evident. Due to their qualitative similarity, we have chosen not to plot here changes in NO_y. A maximum increase in NO_y is largely coincident with a maximum decrease in O_3. The maximum increase in NO_y at a given location is approximately 30-fold for this case.

Several features in these plots are worth noting. First, as is seen in Figures 2 and 3, depletion of ozone is initially greatest at the equator (where the incident flux is highest), becoming greatest toward the poles within a year or so. Larger ozone depletions at the poles are primarily due to the long lifetime of the enhanced NO_y in the polar stratosphere. Figure 3 gives a somewhat exaggerated impression of the effect of depletion at the poles, since ozone is initially high there. The enhanced NO_y, including HNO_3, will lead to an enhancement of nitric acid trihydrate (NAT) polar stratospheric clouds (PSCs). These NAT PSCs facilitate heterogeneous reactions that result in greater ozone depletion by halogen (chlorine and bromine) constituents. This is especially true in the South Polar Region where a stronger polar vortex with colder stratospheric temperatures is in place during the winter. This contributes to an asymmetry that would be peculiar to the present-day configuration of continents. A much larger effect that contributes to the polar asymmetry is the time of year at which the burst occurs, since ozone concentrations at the poles exhibit large seasonal variations. This asymmetry is largely north-south–reversed for a burst in September rather than March (B. C. Thomas et al. 2005, in preparation). We therefore conclude that present peculiarities of continent distribution (including the South Polar vortex) are not a major source of uncertainty in this work.

Around 5–6 months after the burst, there is a short-lived *production* of ozone toward the South Pole. Production occurs at the end of South Polar night when a lack of photolysis has caused accumulation of NO_y constituents that are suddenly photolyzed as the Sun rises, producing O that may then react with O_2 to form O_3.

Globally averaged ozone depletion reaches about 35% (at the start of the long-term run), and a maximum depletion of about 55% occurs first at the equator immediately after the burst, and then again about 15 months after the burst, in the Southern Hemisphere. Significant global depletion (10% or more) lasts for over 5 years after the burst.

Figure 4 (available as an animation online) shows DNA damage estimated by convolving the daily average UVB flux at the ground with a biological weighting function (Setlow 1974; Smith et al. 1980). We include only ozone absorption effects on the UVB flux since the effect of scattering at these wavelengths is comparatively small. We have normalized the plot by dividing the damage by the annual global average damage in the absence of a GRB. Greater DNA damage probability is evident at low latitudes. This is due to a combination of the O_3 depletion effects with the Sun incidence angle, length of day, etc. We have performed other runs with different GRB

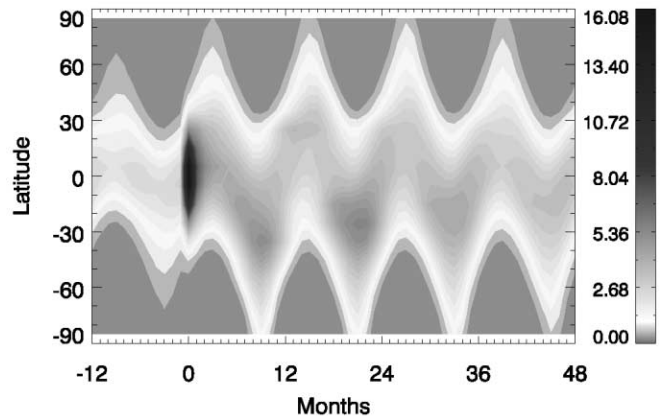

FIG. 4.—Relative DNA damage (dimensionless), normalized by the annual global average damage in the absence of a GRB (the burst occurs at month 0). Note that white is set to 1.0. This figure is also available as an mpeg animation in the electronic edition of the *Astrophysical Journal*.

incidence latitudes, times of year, etc., to be discussed elsewhere (B. C. Thomas et al. 2005, in preparation) and found that the concentration of computed DNA damage to low-mid latitudes is a general feature of the GRB hypothesis. One might think that this damage would be countered by a greater evolved UVB resistance in organisms at low latitudes. However, at least for modern organisms, there is no evidence that temperate zone phytoplankton are any more UVB-resistant than Antarctic plankton (B. Prezelin 2004, private communication). Thus, one might predict that greater ecological damage and extinction would be likely near the equator. It is interesting that the late Ordovician mass extinction (Sheehan 2001) seems to be alone in having recovering fauna preferentially derived from high-latitude survivors (Jablonski 2004).

4. UNCERTAINTIES

Our ionization profiles are computed using simple energy-dependent attenuation coefficients, instead of a full radiative transfer calculation. This technique is implemented following Gehrels et al. (2003) with the primary modification being the functional form of the spectrum. That study found good agreement between their calculations and a full radiative transfer model. We find that ionization due to the gamma-ray input peaks around 30 km elevation, which is in agreement with Gehrels et al. (2003) and Smith et al. (2004).

Effects of prompt redistributed UV are not included in the model. This will both produce and destroy ozone. We have performed a simple test of the magnitude of such effects by increasing the solar flux by 10^4 times for 10 s to simulate the redistributed UV. The resulting ozone depletion is a few percent greater. Also, in some cases, the ionizing fluence from the GRB afterglow may be as large as that from the burst. So, at worst, our results are somewhat conservative. As discussed in Melott et al. (2004) and Dermer & Holmes (2005), there is enough uncertainty in the GRB rate at low redshift that the fluence from the probable nearest burst could be 1 order of magnitude greater than we model here.

A discussion of some uncertainties in the production of NO_y compounds is presented in Melott et al. (2004). In particular, reactions involving exited-state nitrogen atoms, $N(^2D)$, are not included in the atmospheric model. Comparison with simplified, off-line computations using various ratios of $N(^2D)/N(^4S)$ in-

dicate that for our present case, the effect on NO production of including excited-state N atoms is small. Although results depend on the assumed temperature at which the reactions occur, for a reasonable range of temperatures (230–270 K), there is little variation of NO production with increased concentrations of excited-state N atoms, and there is generally less than a factor of 2 difference between the off-line computations and model results. An additional complication is the effect of reactions involving HNO that may limit the production of NO_y. Such reactions are not included in the model, but we estimate that this is a small effect.

The GSFC two-dimensional atmospheric model is empirically based, and its dynamics are not coupled to the significantly changing constituent levels and accompanying heating. This fact introduces some uncertainty in the transport of constituents. As mentioned before, variations due to input latitude and time of year are likely more significant.

5. DISCUSSION

A significant result of our modeling is that even for a short-duration input of radiation, atmospheric effects are large and long-lived. Expectations based on supernova studies indicated that a short-duration input might not have such large effects (Gehrels et al. 2003). The appearance of features such as the localized production of O_3 highlights the need for detailed modeling of the effects of a GRB on the Earth's atmosphere.

Melott et al. (2004) summarizes studies of UVB sensitivity of various organisms (see also Cockell 1999). About 90% of UVB is presently absorbed by atmospheric ozone. Due to the sensitivity of DNA to this radiation, increases of only 10%–30% can have lethal effects on many organisms, especially phytoplankton, the base of the food chain. Ozone depletions in the range of 50%, as seen here, lead to roughly 3 times more UVB at the surface, which is clearly a possible candidate for causing mass extinctions. Of course, we expect additional events from smaller burst fluences over the last gigayear, less intense but still significant for the biosphere.

There are other effects. The event described here could potentially produce of order 0.5 g m^{-2} mean global deposition of nitrates. Biota are generally nitrate-starved, and this deposition may have eased the transition to land, which accelerated after the Ordovician. This nitrate deposition may provide a geochemical signature that could serve as a test of our hypothesis, although this would be difficult because of the extreme water solubility of nitrates. On the other hand, our hypothesis is falsifiable on geochemical grounds. That is, a layer of iridium (associated with impact events) or radioisotopes such as ^{244}Pu (associated with SN events; Ellis et al. 1996) would not be associated with our scenario. Different radioisotopes could be generated by spallation if significant levels of cosmic rays are received (see § 2). However, few would survive to the present from the late Ordovician mass extinction (443 Myr ago).

The Ordovician extinction is associated with a brief glaciation in the middle of a period of stable warm climate. We speculate that there may have been a significant perturbation by the opacity of NO_2, which would cut off a few percent (ranging up to 35% for a month or so during polar fall) of solar radiation (Reid et al. 1978). This would occur primarily at high latitudes, as can be seen in Figure 1. The removal of O_3 (a greenhouse gas) also may cause some cooling, but this effect should be negligible compared to that due to the increase in NO_2. We will provide more detail on these ideas in the near future.

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