Did a gamma-ray burst initiate the late Ordovician mass extinction?

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ABSTRACT

At least five times in the history of life, the Earth experienced mass extinctions that eliminated a large percentage of the biota. Many possible causes have been documented, and gamma-ray bursts (GRB) may also have contributed. GRB (Mészáros, 2001) produce a flux of radiation detectable across the observable Universe. A GRB within our own galaxy could do considerable damage to the Earth's biosphere (Thorsett, 1995; Scalo & Wheeler, 2002; Dar & DeRújula, 2002). Rate estimates (Thorsett, 1995) suggest that a number of such GRB may lie within the fossil record. The late Ordovician mass extinction shows a water-depth dependent extinction pattern that is a natural result

of the attenuation of the strong ultraviolet radiation expected to result from a nearby GRB. In addition, a GRB would trigger global cooling which is associated with this mass extinction.

INTRODUCTION AND HYPOTHESIS

As mass extinctions have become well-documented, interest in them has grown, partly out of concern for our current environmental situation. Extraterrestrial causes have been more seriously considered in recent years, as the extent of their possible impact becomes known. It seems likely that a GRB has affected the Earth, and should have had a substantial effect upon living organisms. We have found patterns of extinction in one event that match expectations of a GRB-initiated extinction.

The consequences of a GRB depend on the observed flux, not the intrinsic total energy, and lack of knowledge of the recent GRB rate is a serious source of uncertainty in estimating the role they may have played in mass extinctions. Most GRB are at high redshift, and the cosmological evolution of the rate is poorly constrained (Weinberg et al., 2001). Results suggest 1-10 GRB per Gy should occur within a few kpc, irradiating the Earth (Thorsett, 1995; Scalo & Wheeler, 2002), although lower estimates may result from assuming proportionality to a strongly evolving star formation rate.

EXPERIMENTAL EXPECTATIONS

Most of the gamma rays are degraded by interaction with the atmosphere, but the prompt UV flux at the surface (Smith et al., 2003) could still exceed existing levels by more than one order of magnitude. Most of the burst energy incident upon the atmosphere goes into ionizing it. If ultra-high energy cosmic rays (mostly protons) accompanied the GRB, they could irradiate the surface with muons, secondaries produced by interaction with the atmosphere, while producing radionuclides by spallation. However, it is unlikely that many beamed cosmic rays would be energetic enough ($>10^{18}$ eV) to travel nearly undeflected by galactic magnetic fields and arrive at Earth coincident with the photon burst. Most cosmic rays will scatter and add a contribution comparable to the background from supernovae. A strong burst of cosmic rays at the Earth would be expected only for isotropic GRB emission with a very hard spectrum. Thus, the instantaneous biotic effects of GRB will be moderate and confined to the facing side of the Earth.

Long-term effects of GRB would spread around the Earth and include ozone layer depletion, global cooling, acid rain, and radionuclide production. The threat considerably exceeds that from supernovae (Gehrels et al., 2003), which are unlikely to occur near enough to produce comparable effects. The chemical effects primarily result from the ionization and dissociation of molecules of N_2 and O_2, the dominant constituents of the atmosphere. The resulting highly reactive products of N_2 dissociation form various oxides of nitrogen. Nitric acid greatly exceeding anthropogenic levels is a probable product (Thorsett, 1995). Global cooling is expected (Reid, 1978) from the absorption of visible light by NO_2. On the other hand, very substantial ozone depletion will result from NO_x constituents, which catalyze conversion (Gehrels et al., 2003) of ozone to oxygen molecules. Ozone absorbs biologically damaging UV radiation before it reaches the surface, so its depletion may have strong consequences. A GRB may have paradoxically produced darkened skies and heightened UV radiation.

Modest increases in UV flux, particularly around 300 nm, can be lethal to a variety of organisms (Kiesecker et al., 2001; Hader et al., 2003), including the phytoplankton which are the basis for the marine food chain as well as oxygen production. UV is attenuated by water, though the precise absorption is heavily dependent upon particulates and dissolved organics (Hader et al., 2003). Penetration depths vary from meters to tens of meters. As would be expected, UV effects on microorganisms have been found to decrease with water depth (Sommer et al., 1999).

EXPERIMENTAL RESULTS SUPPORTING HYPOTHESIS

The late Ordovician is one of the largest mass extinctions in terms of its scale and scope. It appears to comprise two large, abrupt extinction events, separated by 0.5-2 million years (Brenchley et al., 1994; Brenchley et al., 1995), and all major marine invertebrate groups show high rates of extinction during this interval. The late Ordovician is unusual in that many groups like the trilobites, important Ordovician animal groups in terms of their relative abundance, diversity, and geographic range (Droser et al., 1996), go extinct while the more restricted taxa persist (Chatterton & Speyer, 1989). This is counterintuitive because one might predict that (due to stochastic factors) widespread, more abundant groups should be more extinction resistant. One factor that correlates well with likelihood of extinction in trilobites is the amount of time a typical organism spent in the water column. Trilobites that appear to have been pelagic as adults, or are inferred to have had a planktonic larval phase, were much more likely to go extinct (Chatterton & Speyer, 1989). In fact, it appears to not only be whether the larvae were planktonic but the amount of time the larvae spent in the plankton: longer planktonic larval phases, when such are inferred, are associated with increased extinction probability relative to shorter planktonic larval phases. This in turn partly explains the counterintuitive result: marine invertebrate species with a pelagic adult or a planktonic larval type typically had a broader geographic range (Scheltema, 1986). During the late Ordovician, species dwelling in shallow water were also more likely to go extinct than species dwelling in deeper water (Brenchley et al., 1995).

This extinction has been related to alternating global cooling and warming, each associated possibly with what may be the two pulses of the late Ordovician mass extinction (Brenchley et al., 1994; Brenchley et al., 1995; Orth et al., 1986). We do not dispute the role global cooling may have played in mediating this extinction. Instead, we emphasize that there is a natural link between GRB and global cooling. There exists a correlation (Shaviv, 2002) between ice ages and the timing of spiral arm passage, which has been ascribed to increased cosmic ray flux associated with increased star formation and supernovae. We note that since GRB probably arise from star-forming regions and produce opaque nitrogen dioxide in Earth's atmosphere they provide a mechanism for global cooling. Paleoclimate modeling (Herrmann and Patzkowsky 2002; Herrmann et al. 2003) has shown that late Ordovician glaciation would not have proceeded without an impulse such as reduced solar insolation.

We suggest that the late Ordovician extinction may have been initiated by a GRB. The oxygen level of the atmosphere was not greatly different from that of the present (Berner et al., 2003), so that an ozone shield should have been in place. Its destruction would almost certainly involve similar catastrophic consequences to those observed in modern organisms (Kiesecker et al., 2001; Hader et al., 2003). A GRB could have triggered the global cooling, while presenting a host of environmental challenges to life on the planet through the effects of increased radiation reaching the surface, acid rain, etc., followed shortly by global cooling; the result: a one, two punch for life on the planet. Notably, the kind of water depth dependence found in the late Ordovician extinction pattern would emerge naturally from the attenuation of the UV radiation.

ADDITIONAL ARGUMENT IN SUPPORT OF HYPOTHESIS

Supernovae are known to be correlated, probably going off in chain-reactions of star formation and detonation, which produce the "superbubbles" found in the interstellar medium. Given the probable linkage between GRB and supernovae, proximity to one event would suggest an enhanced probability of a second. The late Ordovician extinction seems to have occurred in two pulses about 1My apart.

IMPLICATIONS

This hypothesis suggests that a closer look be taken at the geographical distribution of extinctions in the late Ordovician along the line of what Anstey et al. (2003) have done. A strong initial muon burst might seriously irradiate only one side of the Earth to considerable ocean depth, while the other side would mostly be irradiated by post-burst solar UV due to ozone loss. This suggests an extinction pattern emphasizing depth-dependent extinction predominantly in one hemisphere, with more complete extinction in the other hemisphere. We stress however, that such a pattern is likely only if the GRB emission is isotropic and the event nearby.

While at present we only see strong reasons for associating a GRB with the Ordovician mass extinction, the entire fossil record bears examination in this light. Given the uncertainty in the evolution of the GRB rate, it is possible that such events were involved in more than one mass extinction, or that more distant GRBs could have a stochastic effect, providing small impulses to evolution (Scalo & Wheeler, 2002). A major challenge for astrophysics is to evaluate the likely flux and spectrum of cosmic rays accompanying a burst.

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