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The Hammer of God

"Kali 2 entered the atmosphere just before sunrise, a hundred kilometers above Hawaii. Instantly, the gigantic fireball brought a false dawn to the Pacific, awakening the wildlife on its myriad islands. But few humans; not many were asleep this night of nights, except those who had sought the oblivion of drugs" [11].

This grim description of an asteroid impact by Arthur C. Clarke was inspired by the famous paper "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction" by Nobel Laureate Luis Alvarez and his geologist son, Walter Alvarez [1]. That great extinction episodes in geological history are tightly connected to asteroid/comet impacts is now firmly established [5][2]. Whether impact events are (quasi)periodic or random is not yet clear, and it is also not yet established if some external agent (e.g., a hypothetical Nemesis companion star of the Sun or modulated Oort cloud pertubations via solar oscillations in the Galactic disk; [33][36]) is required to explain the extinction record. While the idea of repeated blows by some "Hammer of God" has found widespread acceptance, a paradigm shift is underway with regards to the way we think about such catastrophes. Was the extinction of the dinosaurs a bad day in our history? From the point of view of the dinosaurs it sure counts as a bad day, but from our present-day perspective we can appreciate how this impact promoted evolutionary changes that benefited humans and other species.

Disturbance Ecology on Grand Scales

Ecology is the study of the interrelationships between organisms and their environment. In the past interactions between predators and prey and between herbivors and plants held the preeminent status among all ecological processes, with the environment merely providing the stage on which the ecological play takes place. This view has changed dramatically in recent decades. The "New Ecology" endowes the environment with an active role. Fires, floods, hurricanes, tornadoes, tsunamis, land-slides, vulcanic eruptions, storms, and lightning strikes are all key agents of the new "disturbance ecology" [37][13]. The destructive power of nature is now viewed as essential for maintaining biodiversity. This new persepective can be expanded by considering that changes in the solar system environment can directly affect the Earth, and that such changes can be driven by gentle or catastrophic events in the solar neighborhood. Long term evolution of the Sun will steadily increase the equilibrium temperatures of the planets on time scales of billions of years (melting the ice caps and eventually boiling the oceans and evaporating the atmosphere), while solar flares occur frequently and occasionally can be so energetic that global planetary atmospheres and the interplanetary space environment become severely polluted with energetic particles that can significantly alter atmospheric chemistry [10] [41][26]. Other dangers lurk just outside the solar system.

As the Sun moves around the Galactic center in a nearly circular orbit the Galactic environment in general changes slowly, but "sudden" (10^{3-4} years) modifications of the planetary environments can take place when the Sun encounters local density fluctuations in the interstellar medium [47] [51] or local field stars [22]. The latter situation can disturb the Oort cloud, increasing the cometary impact rates in the solar system, while the former situation can modulate the properties of the heliosphere and thus the local cosmic ray environment, with potential consequences for planetary climates. Still more damaging could be encounters with very massive stars, black holes, novae, super- novae, and hypernovae (aka Gamma Ray Bursts, GRBs).

Exposure to Nearby Gamma Ray Bursts

The largest energy releases in the Universe due to supernovae and gamma-ray bursts ([31] and [48] discuss both phenomena and their possible connections) do take place with somewhat predictable rates. A core collapse supernova occurs about once every second in the Universe. The Milky Way's present star formation rate is a few solar masses per year, which for a Salpeter-like IMF translates into a Galactic supernova rate of about once per century. The GRB rate is of order 1 day^{-1}, and we know that bursts are truly cosmological (typical redshifts of order unity, with a present record at z $\sim$ 4.5 for GRB000131). Afterglow observations point towards a direct link between GRBs and supernovae so that bursts are also expected to occur in the Milky Way, although with a lower rate. The relative frequency of SNe and GRBs depends on the uncertain beaming pattern of bursts. The observations imply significant beaming corrections, but suggest that GRB rates are still much lower than supernova rates. Long-duration GRBs and SNe are expected to have similar spatial distributions. The amount of energy released into the surrounding medium is of order 1 foe (10^{51} ergs) in both cases, but GRBs focus energy into narrow jets while SNe impact their environments $\sim$isotropically.

Hartmann [25] and Thorsett [45] considered the possibility that a GRB was responsible for the demise of the dinosaurs and perhaps other mass extinctions. Thorsett studied in detail the effect of the gamma-ray flux on Earth's atmosphere, especially the reduction of ozone and the subsequent effects of enhanced solar UV radiation on the surface. Thorsett concluded that the critical distance was $D_{crit} \sim 1$ kpc, and estimated a rate of events closer than this distance of about $1/10^8$ yrs. In 1998 Dar, Laor, and Shaviv [14] investigated the effects of cosmic ray exposure for planet Earth located inside the jet of a galactic GRB. These authors concluded that ozone destruction and radioactive pollution of the Earth could have contributed to mass extinctions, and that biological effects due to ionizing radiation could also have caused the fast appearance of new species. More recently Dar & DeRujula [15] considered the potential dangers from Eta Carina as a future nearby GRB source (concluding that the direction of the possible jet is not aiming at us), and determined that jet-sterilization per life-supporting planet could happen as often as every 100 million years. Such a high rate might provide an answer to Fermi's famous question about alien visitors: "Where are they?". Depressing thoughts along these lines were the theme of the recent NOVA show "Death Star" [35]; nothing seems to sell better than sex and doomsday predictions [30].

A less sensational approach to the possible biological effects of nearby bursts was recently presented by Scalo and Wheeler [39], who investigated in great detail the effects of ionizing GRB radiation on DNA alterations and chemical modifications of the atmosphere. The emphasis of this work is thus not on catastrophes but smaller (more frequent and perhaps

cumulative) events that can alter evolution through enhanced mutagenesis. Scalo and Wheeler estimate the "critical " X-γ-fluence required for a significant increase in DNA alteration, F_{crit} = 5 10^5 ergs cm^{-2}. From observed GRB spectral properties the sphere of influence of a galactic GRB is found to be $\sim$ 10 kpc, so that many galactic GRBs can have a potential impact on Earth's ecology. Scalo and Wheeler estimate that at least one thousand biologically significant Galactic GRB irradiations should have occurred stochastically during the 4.4 Gyr history of life on Earth. The direct effect of one burst (GRB830801) on the ionosphere was recorded via changes in the VLF radio transmissions between distant sites [21], and this event most likely occured at a cosmological distance. Although GRBs are very luminous, their short duration provides a moderating factor in comparison to other potential sources of ionizing radiation (massive stars, supernovae, etc), and causes only one half of the Earth to be affected in any given exposure.

Exposure to Nearby Supernovae

The rate of nearby Galactic supernovae is a rather uncertain quantity, and estimates date back to the sixties [43]. The impact of a close supernova on the biosphere was considered in the seventies [38][27][49] and subsequent studies zoomed in on particular supernovae (e.g., Vela [8], and Geminga [23]) or nearby star forming regions (Sco-Cen [4]). The potential identification of such events through specific isotopic anaomalies (e.g., ^{60}Fe) was pointed out by Ellis and collaborators [18][20]. A recent search for ^{60}Fe anomalies in deep-ocean ferromanganese crust samples was sucessful [29] and estimates of the distance and epoch of the putative supernova give D $\leq$ 30 pc and age $\leq$ 5 Myrs [20], based on standard yields of M_{ej}(^{60}Fe) $\sim$ 10^{-5} $M_\odot$ [46]. The decay of ^{60}Fe (mean life $\sim$ 2 Myrs) produces gamma-ray lines at 1.17 MeV and 1.33 MeV. The diffuse glow of the galactic disk from the many supernovae that occur during a few mean life times may soon be detected with INTEGRAL, an ESA mission to be launched later this year [50] [42]. Tracing the orbits of the Sun and nearby stars back in time Benitez et al. [4] find that massive stars born in the Sco-Cen association produced supernovae at the right time and distance to be responsible for the ^{60}Fe observed in the ocean crust. According to these authors $\sim$ 2 Myrs ago a "Sco-Cen supernova" as close as D $\sim$ 40 pc could have done serious damage to the Earth' ozone layer, provoking or contributing to the Pliocene-Pleistocene boundary marine extinction. A very recent (or perhaps near future) supernova impact may be associated with "Vela-Junior" [3], for which ^{44}Ti gamma-ray line observations [28] were used to argue for a distance of D $\sim$ 150 pc and an age of t $\sim$ 700 yrs.

While dramatic events such as the demise of the dinosaurs and other mass extinctions may in some cases be linked to nearby supernovae [10], more moderate alterations of evolutionary paths through the enhanced UV exposure were only recently considered in detail [40]. Core collapse supernovae launch a strong shock that propagates through the star for a few hours, depending on the progenitor size and mass and ejecta energy. The shock-breakout leads to a short UV-flash [16] [19][7] that delivers of order 10^{47} ergs in the 200-300 nm UV band. Scalo et al estimate that a "critical" fluence for enhanced mutagenesis in this crucial energy window is $F_{crit} \sim$ 600 ergs/cm^2. Taking into account absorption in the atmosphere the relevant value at the top of the atmosphere is about three times as large. The critical distance for shock breakout UV-flashes to affect the biosphere is thus of order 1 kpc. The effect of galactic extinction must also be taken into account, as emphasized by Scalo et al. In the UV band considered here the average differential midplane UV-extinction is $\partial_r A_{UV} \sim$ 5 mag kpc^{-1}.

In addition, one should consider the spatial distribution of the absorbing dust relative to the spatial distribution of supernovae.
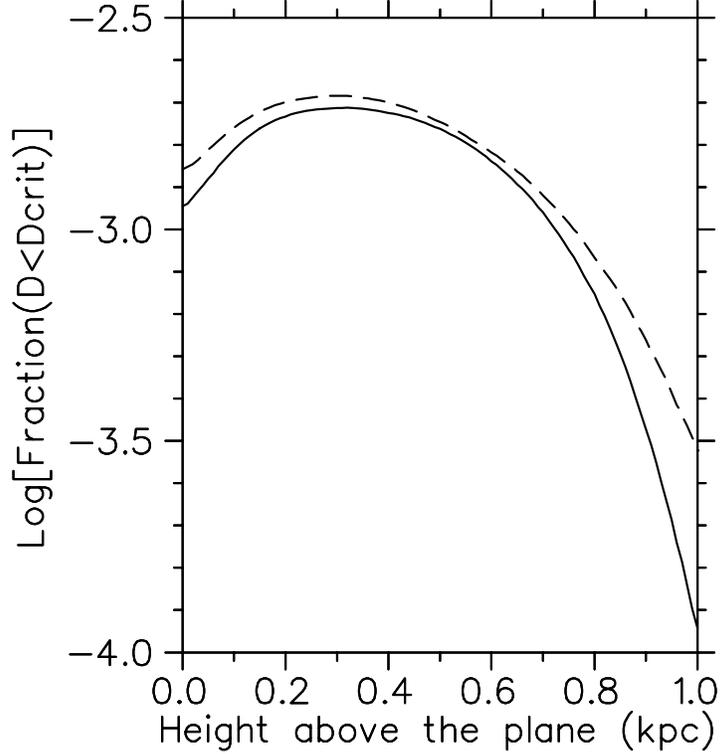

Figure 1: The fraction of Galactic Supernovae closer than the critical distance (see text) as a function of position above the midplane. The solid line assumes the same vertical profile for dust and supernovae, while the dashed curve is for a supernova distribution with doubled scale height.

What is the frequency of supernovae that generate UV fluences at Earth that exceed the critical value? A galaxy-wide star formation rate of a few solar masses per year is associated with a supernova rate of a few events per century (many papers have been written about the value of "few" in both of these quantities). If the fraction of events closer than D_{crit} is f, the time between "events that cause a disturbance" is $\Delta T \sim 100/\text{few } f^{-1}$ years, where "few" is about $1-3$ [44]. We find that f is of order 10^{-3}, so that dangerous UV-flashes from nearby supernovae occur as often as every $\sim$100,000 years. Scalo et al. provide an estimate of this time scale as a function of fluence and peak flux.

We now consider a modification of these rate estimates due to the solar motion in the Galaxy. The Sun is currently located ~ 10 pc above the midplane (this number is uncertain, but everyone agrees that it is not zero [32][24][34][12]), but its perpendicular velocity relative to the local standard of rest W $= 7.2 \pm 0.4$ km/s [6] will eventually carry us to a maximal height H ~ 100 pc (depending on the galactic mass model) above the plane. The sun, like most stars, will spend most of its time above the Galactic dust layer, so that this effect should be included in estimates of the extinction to supernovae. The figure shows the variation of f with height above the Galactic plane. For the Sun the change in Δ T is less than a factor two, but for planets around high-velocity stars the effect can be significant (making damaging

exposure ten times less frequent if vertical motion carries the star to z ∼ 1 kpc above the plane. The effect seen in the figure is due to the exposure asymmetry (events above/below the plane) for small heights but simply the result of larger distances from supernovae as the star moves away from the disk. For heights well in excess of 1 kpc none of the galactic supernovae is ever close enough to have an effect. As the stars oscillate in the Milky Way with periods of order $50-100$ Myrs plane passages would lead to increased exposure, but less time is spend in the "critical midplane zone". A Monte Carlo simulation using these constraints could evaluate the time-averaged UV-exposure as a function of position and kinematics in the Galaxy.

We also investigated the effects of a larger scale height of supernovae relative to the dust (dashed line in the figure). The standard model assumes an exponential scale height of $H_z = 60$ pc for both components, while the model with larger extent of the supernova layer assumes $H_z = 120$ pc. The effect of "puffing up" the SN distribution is reduced extinction and thus a slightly larger fraction of critical events, but the effect is obviously not very strong. The radial distribution of supernovae probably is a more critical parameter. It is however rather uncertain and we describe it by a gaussian function, centered at R = 4 kpc, the location of the well known molecular ring [6]. If the width of this gaussian drops below 3 kpc, the fraction of "deadly SN" decreases rapidly. Clearly, a delta function at R = 4 kpc generates no SN close enough to damage the biosphere. If the gaussian width exceeds 3 kpc, the fraction saturates as the local SN density profile becomes flat (as was assumed by Scalo et al.). While the time between SN that are "too close for comfort" depends on many properties of the Galaxy, the solar orbit, the shock breakout properties, and assumptions about what constitutes a biologically significant exposure, the perhaps surprising fact remains that close calls happened many times along our path around the galactic center.

Conclusions and Outlook

Can a nearby GRB or Supernova ruin your day ? You bet! Does this happen frequently? Yes and no, depending on your point of view. On a present-day human history time scale the answer is no (fortunately), but on a long-term- history-of-life time scale the answer is yes. Over the past billions of years there must have been a large number of close encounters of the undesired kind - UV jolts from supernovae and GRBs, and longer exposures to passing luminous and hot stars. Disturbance ecology is driven by events taking place on Earth and in the immediate Galactic environment of the solar system. Mutagenesis can be stimulated by exposure to external UV sources, and despite the long time intervals between events (ten thousand years to perhaps millions of years) these "rare" events may have domiated the path of evolution on Earth as well as other inhabited planetary systems throughout the Galaxy. The killing of the dinosaurs was indeed spectacular, but perhaps more impressive is the realization that the evolution of life throughout the Universe is so closely intertwined with the violent history of the Universe. Once every second a supernova and once every minute a GRB sends a UV flash into some galactic environment, jolting mildly or vehemently life in its path. It happened many times in Earth's history, and it will happen again. We hope that the next nearby jolt in our path contributes to a better global future for most lifeforms on Earth.

Acknowledgements

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