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Could a nearby supernova explosion have caused a mass extinction?

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ABSTRACT We examine the possibility that a nearby supernova explosion could have caused one or more of the mass extinctions identified by paleontologists. We discuss the possible rate of such events in the light of the recent suggested identification of Geminga as a supernova remnant less than 100 parsec (pc) away and the discovery of a millisecond pulsar about 150 pc away and observations of SN 1987A. The fluxes of γ-radiation and charged cosmic rays on the Earth are estimated, and their effects on the Earth's ozone layer are discussed. A supernova explosion of the order of 10 pc away could be expected as often as every few hundred million years and could destroy the ozone layer for hundreds of years, letting in potentially lethal solar ultraviolet radiation. In addition to effects on land ecology, this could entail mass destruction of plankton and reef communities, with disastrous consequences for marine life as well. A supernova extinction should be distinguishable from a meteorite impact such as the one that presumably killed the dinosaurs at the "KT boundary." The recent argument that the KT event was exceedingly large and thus quite rare supports the need for other catastrophic events.

During the 600 million years (Myr) or so since life on Earth emerged from its murky pre-Cambrian beginnings, it has been subjected to five major mass extinctions, the "Big Five," as well as a spectrum of lesser extinctions (ref. 1 and references therein). These have been the subject of intensive research, particularly during the past decade. Many theories have been advanced to explain one or more of these extinctions, including both terrestrial and astrophysical events. Among the former, one should mention massive volcanic episodes. Among the latter, particular mention should be made of meteorite impacts, whose advocacy by Alvarez *et al.* (2) stimulated much research. The famous dinosaur-killing mass extinction at the end of the Cretaceous, which began the tertiary era (the so-called "KT boundary"), has been convincingly identified with such a meteorite impact, while the record-holding Permian extinction might have been caused by the volcanic episode that created the Siberian traps. Advocacy of these volcanic and meteoritic mechanisms has been aided by the availability and tangibility of supporting evidence in the forms of large lava flows and contemporary volcanoes on the one hand and impact craters and Earth-crossing asteroids on the other hand.

Recently, Sharpton *et al.* (3) have argued that the KT boundary event was due to an exceedingly large object. They estimated that this was the largest such impact in the last 4 billion years. Yet, other biological mass extinctions of comparable or large magnitude appear to have occurred during the past 600 Myr. This supports the argument that more than one mass extinction mechanism exists. Astrophysical mechanisms have frequently been cited as possible candidates. Examples of astrophysical origins of mass extinctions include variations in the solar constant, supernova explosions, and meteorite or comet impacts that could be due to perturbations of the Oort cloud. The first of these has little experimental support. Nemesis (4), a conjectured binary companion of the Sun, seems to have been excluded as a mechanism for the third,§ although other possibilities such as passage of the solar system through the galactic plane may still be tenable. The supernova mechanism (6, 7) has attracted less research interest than some of the others, perhaps because there has not been a recent supernova explosion in our Galaxy to concentrate our minds, and perhaps because the prospective lethality of a nearby supernova explosion has not been fully appreciated. Also, supernova rates are certainly too low to explain all of the extinction events (8).

We think that there are at least four reasons for reconsidering now the supernova mechanism for at least one mass extinction. One is that extinction studies have advanced greatly since the supernova mechanism was last discussed, and the need for multiple mechanisms is now reasonable. Another is that the possible identification (9) of the Geminga γ-radiation source with a supernova remnant ≈60 parsec (pc) away (1 pc = 3.09×10^{16} m) which apparently exploded ≈300,000 years ago, shows that such nearby events are not fanciful and provides us with possible new hints about rates, as does the recent discovery of a millisecond pulsar PSR J0437-4715 ≈150 pc away. [We are well aware that the Geminga explosion location identification is not unique (10), so caveats on rates are obviously appropriate (8).] A third reason is that the recent detailed observations of SN 1987A clarify the characteristics of supernova explosions (11). Finally, there has been much recent work on the biological effects of ozone depletion, motivated by the observed Antarctic hole (12). It was Ruderman (13) who first pointed out the possible effect of a supernova on the ozone layer, and this seems to us potentially the most catastrophic effect of a nearby supernova explosion.

There is much uncertainty on supernova rates (8, 14). We believe that it is reasonable to estimate that one or more supernova explosions are likely to have occurred within 10 pc or so of the Earth during the Phanerozoic era—i.e., during the past 570 Myr since the sudden biological diversification at the start of the Cambrian. Since stars' orbital motions around the Galaxy can separate them by up to 10 kpc over 100 Myr, the remnants of any such supernova explosions would not be very close today. On the other hand, the space within 10 pc or so of Earth should contain remnants of explosions that took place within the past 100 Myr up to 10 kpc away. The best estimate we can offer of the fluxes of energetic electromagnetic and charged cosmic radiation from a supernova explosion within 10 pc indicates that the latter would have destroyed the Earth's ozone layer over a period of ≈300 years or so. Recent studies, motivated by the appearance (12) of the ozone depletion in the Antarctic, indicate that the increase in ultraviolet radiation due to ozone removal could have a negative effect (15) on phytoplankton, and hence on the rest of marine life, from

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Abbreviations: Myr, million years; pc, parsec.

[§] Except possibly for a small region of parameter space (5).

zooplankton through to benthic life, in addition to the obvious threat to terrestrial life. Since reef communities are also dependent on photosynthesizing organisms, they could also have been severely damaged or disrupted by the ozone hiatus, with correspondingly severe consequences for the diverse marine life they support. We also note that a shutdown of photosynthesis due to solar ultraviolet irradiation could well be followed by a greenhouse episode.[¶]

We first discuss the possible rate of supernova explosions in the light of suggestions such as Geminga and other recent developments. Many authors have estimated that there are explosions every 10–100 years in our Galaxy, which contains $\approx 10^{11}$ stars. We draw the reader's attention in particular to a recent analysis (14) of the amount of oxygen in the Galaxy, which originates from supernova ejecta and seems to require an average explosion rate of about 1 every 10 yr, if all the ejecta are retained in the Galaxy. However, the local hole possibly due to Geminga extends much further into the less dense region away from our local spiral arm,[‖] raising the possibility that material ejected out of the galactic plane might escape altogether. In this case, explosions at average intervals even shorter than 10 yr could be required, despite their observational rarity in other galaxies. This is conventionally ascribed to obscuration, but it could also be due to the same reason that SN 1987A was relatively dim—namely, the previous loss of its outer envelope. SN 1987A would not have been seen in most surveys if it had occurred in a distant galaxy. [Although van den Bergh (8) cautions that the number of supernova progenitor stars ($M > 8M_\odot$) may not be sufficient for such rates, his argument fails to note fully the difficulty in accurately estimating the number of such stars due to their short lifetimes and their formation in obscured regions of the Galaxy.] Taking an average stellar density of 1 pc^{-3}, a supernova rate of 0.1 yr^{-1} corresponds to one explosion every 240 Myr on average within 10 pc of the Earth. [This is about 3 times van den Bergh's rate but in good agreement with Kocharov's (17) rate estimate.] Some might consider this rate optimistic (or pessimistic, depending on one's point of view), but scaling from Geminga (albeit with a statistic of one!) suggests an even larger rate: assuming a distance of 60 pc and an age of 300,000 years inferred from the rate of deceleration of Geminga's spin,[**] one finds an explosion within 10 pc every 70 Myr or so. A relatively high rate is also indicated by the recent discovery (18) in a partial sky survey of the millisecond pulsar PSR J0437-4715 $\approx$150 pc away, with a spin-down age of $\approx 10^9$ years. Assuming that we are in its beam cone, and that this subtends about 10^{-2} to 10^{-3} of the full solid angle, simple scaling indicates that a supernova explosion could occur within 10 pc of us every 500 Myr or so. Inferring supernova rates from pulsars is known to be quite uncertain, but we feel the consistency is nonetheless interesting. We conclude that, while much uncertainty exists, it is very plausible that there have been one or more supernova explosions within 10 pc of the Earth during the Phanerozoic era.

Three more comments on galactic supernovae might be useful. One is that they mainly occur in the spiral arms of the Galaxy, so that the rate should not be expected to be uniform in time. The Earth passes through a spiral arm once every 100 Myr or so, with each passage taking $\approx$10 Myr, although it is unclear whether this would lead to any discernible periodicity in nearby supernova events. In any case, this period does not coincide with the reported 26- to 30-Myr periodicity of the bulk of extinction events: anyway, we do not expect supernova extinctions to constitute the bulk of the known extinctions (1). A second comment is that the relative velocities of stars in the Galaxy mix them up very thoroughly on a time scale of $\approx$100 Myr: for example, Geminga's proper motion corresponds to a transverse velocity of $\approx$30 km/s, sufficient to take it 10 kpc away from us during the next 100 Myr. This means that the remnants of any nearby explosions would be far away by now. It also means that no star now in the solar neighborhood is an obvious threat to our survival. Third, if we are right, the solar neighborhood should be populated with remnants of explosions that took place long ago and far away, and it would be interesting to devise an observational program to scan for them, perhaps in x-ray or radio bands, as a check on our proposal.

We now present some crude estimates of the likely terrestrial effects of a nearby supernova explosion. Because of the simple $1/R^2$ scaling law for intensity, it is generally agreed that the heating of the Earth would not be significant and that the optical brightness of a supernova at 10 pc would not greatly harm the ecology. It is also easy to convince oneself that supernova ejecta would not have a significant effect on the apparent solar constant. The most important effects are likely to be those of ionizing radiation, which falls into two categories. There is a burst of neutral electromagnetic radiation that arrives over a period of a few months and a larger and longer burst of charged cosmic ray particles. In line with previous estimates (13, 19–21), we assume that the neutral component has a total energy output of 3×10^{46} ergs, and the charged component has an output of 10^{50} ergs. The period over which the latter are emitted is unclear,[††] but the charged cosmic ray burst is in any case spread out by diffusion through the inhomogeneous galactic magnetic field. Taking an angular persistence length of 1 pc for the latter, one estimates a diffusion time of $3D_{\text{pc}}^2$ yr (19, 20) where D_{pc} is the distance of the supernova measured in pc. The average flux of neutral ionizing radiation per unit surface area normal to the Earth's surface is therefore estimated to be

$$\phi_{\text{n}} = \frac{3 \times 10^{46}}{16\pi D^2}\ \text{ergs/cm}^2 \simeq 6.6 \times 10^5 \left(\frac{10}{D_{\text{pc}}}\right)^2 \text{ergs/cm}^2, \qquad [1]$$

for about a year, whereas the average normal flux of charged cosmic rays is estimated to be

$$\begin{aligned}\phi_{\text{cr}} &= \frac{10^{50}}{16\pi D^2(3D_{\text{pc}}^2)}\ \text{ergs}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}\\ &\simeq 7.4 \times 10^6 \left(\frac{10}{D_{\text{pc}}}\right)^4 \text{ergs}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}, \qquad [2]\end{aligned}$$

for a duration of $\approx 3D_{\text{pc}}^2$ yr. For comparison, the ambient cosmic ray flux is 9×10^4 ergs·cm^{-2}·yr^{-1}, which produces a radiation dose at the Earth's surface of 0.03 R/yr and 10^7 NO molecules·cm^{-2}·yr^{-1} after diffusion throughout the stratosphere. We doubt that an increase in the cosmic ray-induced radiation dose by 1 or 2 orders of magnitude, as suggested by the numbers (1, 2) for a supernova 10 pc away, would be catastrophic for the global ecology, although we cannot exclude the possibility that it would be harmful to some key organisms. However, we do believe that a dramatic increase in NO production would have catastrophic implications for the Earth's ozone layer and hence for many life forms.

We use the analysis of Ruderman (13), who was the first to consider the effect of a supernova explosion on the Earth's ozone layer, to estimate the increase in NO production and the

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[¶] Possible damage to DNA is also a cause for concern (16).

[‖] On the other hand, Frisch (10) has argued that the Geminga remnant is due to an explosion in Orion and is unrelated to the local bubble, so uncertainties obviously exist.

[**] It would be interesting to consider whether any trace of the Geminga explosion could be found as an isotope anomaly in ancient cores (17). We will explore this in more detail in a subsequent paper.

[††] Models of cosmic ray acceleration predict ranges from 10^1 to 10^5 yr or more (22).

consequent ozone destruction. Ionizing radiation is estimated to produce NO at a rate of about

$$R_{\mathrm{NO}} = 9 \times 10^{14}\left(\frac{\phi}{9\times 10^{4}}\right) \times \left(\frac{13}{10+y}\right)\ \text{molecules}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}, \qquad [3]$$

if NO dominates over NO_2 in the stratosphere, as we expect, where y is the NO abundance in parts per 10^9. The first factor in Eq. **3** is the present rate of NO production by cosmic rays, the next is the ratio of supernova radiation to cosmic radiation, and the last is a ratio of efficiencies, assuming a present NO abundance of 3 parts per 10^9. We assume for simplicity that the electromagnetic and cosmic radiation from a supernova ionize at the same rate per erg of incident energy as do present-day cosmic rays. We therefore expect that the charged cosmic radiation from the supernova would produce significantly more NO than would the electromagnetic radiation, in an amount

$$R_{\mathrm{NO}} = 7.4 \times 10^{16}\left(\frac{10\ \mathrm{pc}}{D}\right)^{4} \times \left(\frac{13}{10+y}\right)\ \text{molecules}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}, \qquad [4]$$

during $\approx 3D_{\mathrm{pc}}^2$ yr. The residence time for NO in the stratosphere before diffusing out is thought to be 2–6 yr. Taking a mean of 4 yr, and dividing R_{NO} by the stratospheric column density of 5×10^{23} molecules per cm^2, we find that the supernova cosmic rays would contribute,

$$y_{\mathrm{cr}} = 600\left(\frac{13}{13+y_{\mathrm{cr}}}\right)\left(\frac{10}{D_{\mathrm{pc}}}\right)^{4} \simeq 88\left(\frac{10\ \mathrm{pc}}{D}\right)^{2}, \qquad [5]$$

to the NO abundance in parts per 10^9. Assuming an altitude-independent abundance of NO, Ruderman (13) gave the following approximate formula for the ratio of O_3 to present ambient O_{3_0}:

$$F_0 = \frac{O_3}{O_{3_0}} = \frac{\sqrt{16+9X^2}-3X}{2}, \qquad [6]$$

where $(3 + y_{\mathrm{cr}})/3$ is the ratio of NO_0 to present ambient NO. Eq. **6** may be approximated by $4/3X \simeq 4/y_{\mathrm{cr}}$ for large $X(y_{\mathrm{cr}})$.

The resulting increase in the penetrating flux of solar ultraviolet radiation, integrated over the duration of the cosmic ray burst, is

$$(f^{F_0} - f) \times (3D_{\mathrm{pc}}^2), \qquad [7]$$

where f is the fraction of the incident solar ultraviolet radiation that normally reaches the Earth's surface. In the case of radiation with a wavelength of 2500 Å, which has the maximum relative effectiveness for killing *Escherichia coli* bacteria and a high relative efficiency for producing erythema (sunburn), f is $\approx 10^{-40}$ today, so a reduction of the O_3 layer to 10% of its present thickness would increase the flux of ultraviolet radiation by 36 orders of magnitude. For nearby supernovae, the integrated increase in the penetrating flux can be approximated by

$$10^{-\left(\frac{D}{7\ \mathrm{pc}}\right)^{2}} \times 300\left(\frac{D}{10\ \mathrm{pc}}\right)^{2}. \qquad [8]$$

We see that the flux increase is probably negligible for supernovae much more than 10 pc away, while their rate is probably negligible for supernovae much closer than 10 pc; hence our focus on 10 pc as the critical distance around which a supernova explosion is most likely to have caused a mass extinction, which we have taken as a reference in our flux estimates above.

A species may become extinct either because it is killed directly (for example, by sunburn or a radiation overdose) or for some indirect reason (for example, a change in the environment, such as global cooling or warming, or the disruption of its food supply). A nearby supernova explosion could affect many species directly via the solar ultraviolet radiation admitted after destruction of the ozone layer. These would need to be studied on a case-by-case basis. Apart from this increase in radiation, we do not expect any dramatic environmental effects resembling those caused by a large meteorite impact or massive volcanism. Instead, we focus here on the possibility of mass extinction caused by a disruption of the food chain at a low level, specifically by the destruction of photosynthesizing organisms. This has already been discussed as an important side effect of a large impact or volcanic episode. In our case, it is clear that any photosynthesizing organism must try to "see" the Sun, and the absence of an ozone layer means that it will see and be affected by ultraviolet radiation as well. Photosynthesis manifests both a diurnal and an annual cycle. An ozone hole induced by a supernova explosion 10 pc away would last for ≈300 yr (to within an order of magnitude) and hence act over many annual cycles—indeed, longer than the lifetimes of most present-day fauna.

Half of photosynthesis today is due to phytoplankton, and the effect on them of ultraviolet radiation has recently been studied in connection with the ozone hole in the Antarctic.‡‡ A decline in the rate of photosynthesis of Antarctic plankton exposed in plastic bags has been demonstrated (15). The possible importance of radiation effects on polyethylene as a factor in this particular experiment has been emphasized (23), but these objections are not seen as conclusive (24). Therefore, we feel that this experiment makes an *a priori* case that a long-term exposure to the full ultraviolet radiation of the Sun could shut down marine photosynthesis and hence cause a mass extinction of marine life, from phytoplankton to zooplankton and so on all the way to benthic organisms. We note that a shutdown of photosynthesis due to ultraviolet irradiation from the Sun could lead indirectly to a greenhouse episode, due to a buildup of CO_2. We note also that reef communities, which are known to have been destroyed during mass extinctions, are particularly exposed to solar ultraviolet radiation and depend directly on photosynthesizing organisms, and we remind the reader that reef communities are the source of much of the marine biodiversity. Thus, the effects of a nearby supernova explosion would not be limited to terrestrial organisms and might even have had a larger effect on the marine community. Could such an event have been responsible for the Permian mass extinction that finally killed the trilobites?

We conclude that recent observations of Geminga, PSR J0437-4715, and SN 1987A strengthen the case for one or more supernova extinctions during the Phanerozoic era (or, to state it more conservatively, astrophysical arguments do not exclude such a hypothesis). A nearby supernova explosion would have depleted the ozone layer, exposing both marine and terrestrial organisms to potentially lethal solar ultraviolet radiation. In particular, photosynthesizing organisms including phytoplankton and reef communities are likely to have been badly affected. We believe that the potential signatures of supernova extinctions merit further study.

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‡‡As we have already noted, damage to DNA is also a cause for concern (16).

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