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OZONE CONTROL OF BIOLOGICAL ACTIVITY DURING EARTH'S HISTORY, INCLUDING THE KT CATASTROPHE. W. R. Sheldon, University of Houston, Houston TX 77204-5506, USA.

There have been brief periods since the beginning of the Cambrian some 600 m.y. ago when mass extinctions destroyed a significant fraction of living species. The most widely studied of these events is the catastrophe at the KT boundary that ended the long dominance of the dinosaurs. In addition to mass extinctions there is another profound discontinuity in the history of Earth's biota, the explosion of life at the end of the Precambrian era, an episode that is not explained well at all. For some 3 b.y. before the Cambrian, life had been present on Earth, but maintained a low level of activity, an aspect of the biota that is puzzling, especially during the last two-thirds of that period. During the last 2 b.y. before the Cambrian, conditions at the Earth's surface were suitable for a burgeoning of the biota, according to most criteria: The oceans neither boiled nor were frozen solid during this time, and the atmosphere contained sufficient O for the development of animals. The purpose of this paper is to suggest that mass extinctions and the lackluster behavior of the Precambrian biota share a common cause: an inadequate amount of ozone in the atmosphere.

Calculations of atmospheric ozone O_3 have been made with the concentration of O_2 in the atmosphere as a variable parameter [1,2], but with the solar spectrum at the top of the atmosphere assumed to be that observed at present. On the basis of these calculations it is of interest to note that the present ozone atmosphere is only some 30% above the critical value of 7×10^{18} O_3 cm^{-2}, a level that provides a "full screen" for the biota; however, an O_2 concentration only 10% of the present atmospheric level (PAL) creates an ozone atmosphere only 20% below the critical value. Consequently it has been assumed that when the O_2 concentration reached the neighborhood of 10^{-1} PAL, the biota found an environment on the Earth's surface relatively free of degradation from solar ultraviolet (UV) radiation. Here that concept is questioned and a scenario is described in which a robust O_2 atmosphere could be present, but an O_3 atmosphere anywhere near the critical value would not be formed.

Present concern for the Earth's ozone layer is focused on chemical processes in the atmosphere that destroy O_3; the ozone production rate is constant and not considered to be a potential problem. In the geologic past such was certainly not the case and the main point of this paper is that during the Earth's history the O_3 production rate has been the controlling factor for the biota. Specifically, it is suggested that cometary activity during the Precambrian and comet showers during mass extinction events provided a supply of volatile material to the inner solar system that selectively absorbed UV photons capable of photolyzing the O_2 molecule (and thus precluded O_3 production); at the same time the solar flux at near-UV wavelengths arrived at Earth unattenuated, resulting in an extremely harsh environment for the biota at the Earth's surface and at ocean depths down to several tens of meters.

The comets under consideration consisted of volatile material that accumulated in the region of the nebular disk beyond Jupiter's orbit. Then gravitational perturbations by the four giant planets redistributed a portion of these cometary bodies to form the Oort comet cloud at the outer boundary of the solar system [3]. At the same time a much larger number of these bodies were expelled from the solar system, or were disrupted and vaporized by passing in the vicinity of the Sun [4,5].

In order to estimate the amount of cometary volatile material that is required to have a critical effect on O_3 production in the atmosphere it is assumed that the rate of O photolysis ($O_2 + h\nu \rightarrow O + O$) required for O_3 production is proportional to the flux of photons in the extreme UV that drive the reaction; further it is assumed that a reduction of the O_3 production rate of $\frac{1}{e}$ of its present value would result in an environment sufficiently harsh at the Earth's surface to account for the Precambrian biota or mass extinctions. In the present atmosphere the flux of 200-nm photons is reduced to $\frac{1}{e}$ of its value at the top of the atmosphere by $\sim 10^{23}$ O_2 molecules per cm^2. However, the cometary volatile material would consist of water (H_2O) and ammonia (NH_3), molecules with UV absorption cross sections greater than that of O_2 by factors of 10 and 10^6, respectively [2]. Thus an average concentration of $\sim 7 \times 10^8$ cm^{-3} of H_2O, or $\sim 7 \times 10^3$ cm^{-3} of NH_3, would be required along the path connecting the Earth and the Sun. If the cometary material is constrained to a disk 0.1 AU thick the total amount of H_2O would be 2×10^{25}g, or 10^{20}g of NH_3. Comparing the collision cross sections of the Earth and the disk (a factor of 5×10^7), it is concluded that during the same period of time cometary transport would deposit 4×10^{17}g H_2O on Earth, or 2×10^{12}g NH_3. Assuming a residence time of one year for vaporized material in the disk (corresponding to an average velocity of 50 km s^{-1} for the outward transport of the vapor), during the 3×10^9 years of cometary activity in the Precambrian 1.2×10^{27}g H_2O, or 6×10^{21}g NH_3, would have been deposited on Earth.

It is appropriate to consider two aspects of this proposed scenario for the effect of comets on the history of Earth's biota: whether it is possible and what, if any, further conclusions would result. The most direct quantitative comparison involves the total amounts of H_2O or NH_3 predicted to have been deposited on Earth by cometary activity [6,7]. The amount of H_2O alone that would be required exceeds the amount on Earth by more than 2 orders of magnitude, but the amount of NH_3 required is about equal to the mass of Earth's atmosphere. Thus the proposed scenario seems to meet the zeroth order test, epsecially where NH_3 is concerned. However, it should be noted that the required amount of volatile material could be an overestimate, since the absence of an O_3 atmosphere for perhaps only 1% of the time during the Precambrian could suffice to suppress the development of the biota on the Earth's surface. Another consideration is the fact that solar luminosity was less during the

Precambrian era. Also, the amount of cometary volatile material that has been deposited on Earth may be more than is found at present, since some of the volatile material may have been removed by impact erosion. In addition, the UV absorption cross sections of cometary H_2O and NH_3 may be larger than the values measured in the laboratory, since in comets they could be in the form of cluster molecules [8]. Finally, the continuous introduction of H_2O and NH_3 at the top of the atmosphere would not only supress O_3 production by UV absorption, but the photolyzed products would catalytically destroy O_3 by the well-known reactions at work in the stratosphere at present [9].

Since suppression of the O_3 atmosphere by comets in the inner solar system appears to be possible, it is of interest to note that the same mechanism would resolve two other current problems involving the history of Earth and Mars. The likelihood of NH_3 in the Precambrian atmosphere was suggested [10] in order to provide the necessary greenhouse effect when solar luminosity was less than its present value, and thus reconcile calculated ocean temperatures with the observation that the oceans had not frozen. However, calculation of NH_3 photolysis [11] indicated a lifetime for NH_3 in the atmosphere that was significantly less than that which was required. The presence of NH_3 and H_2O in the inner solar system according to the scenario presented here could reduce the rate of NH_3 photolysis in the Earth's atmosphere to a level that would permit the small amount of NH_3 that had been suggested [10]. In a similar way the efficient greenhouse nature of NH_3, in conjunction with its shielding from solar UV radiation by cometary outgassing in the inner solar system, could account for the warmer temperatures on Mars that are needed to explain the fluvial features that have been observed there.

To summarize the main suggestion proposed here: Discontinuities in the history of Earth's biota can be explained by the single unifying suggestion that low levels of O_3 production are controlled by cometary activity. Precambrian biological activity is explained along with mass extinctions. Where mass extinctions since the Cambrian are concerned, comet showers from the remnants of the nebular disk lasting for thousands to millions of years provide a model consistent with the paleontological record, which shows biological degradation lasting for similar periods and becoming increasingly destructive with time until the event suddenly ends. Since the model proposed here appears to answer some outstanding questions it should be investigated further.

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THE CRASH OF P/SHOEMAKER-LEVY 9 INTO JUPITER AND ITS IMPLICATIONS FOR COMET BOMBARDMENT ON EARTH. E. M. Shoemaker and C. S. Shoemaker, Lowell Observatory, 1400 West Mars Hill Road, Flagstaff AZ 86001, USA.

Periodic Comet Shoemaker/Levy 9 will impact Jupiter in late July 1994 [1,2]. The comet, which broke into more than 20 telescopically detectable fragments [3] when it passed within the Roche lobe of Jupiter on July 8, 1992, is captured in a highly eccentric orbit about Jupiter. The 21 recognized nuclei will be spread out in a train of the order 7×10^6 km long at the time of impact, and the impacts will be spread in time over about 5 1/2 days centered on about July 21.2 UT [4]. In addition to the train of recognized bright nuclei, the comet consists of "wings" of unresolved bodies that are the source of a very broad composite dust tail. The linear extent of the wings is about an order of magnitude greater than that of the train of recognized discrete nuclei. Collision of the wings will be spread in time over several months. Thus the impact of P/S-L 9 with Jupiter will be an event of appreciable duration.

Sizes of the recognized nuclear fragments of P/S-L 9 are not yet firmly established. Photometry from high-resolution images acquired by the Hubble Space Telescope suggests that the 11 largest nuclear fragments range from 2.5 to about 4.3 km in diameter, and that the precursor body, before breakup, was about 8 km in diameter or larger [5]. A preliminary dynamical solution for the development of the observed train of nuclei by Scotti and Melosh [6] suggests that the precursor body was only about 2 km in diameter. However, a later solution by Chodas and Yeomans [4], based on orbits of the individual nuclei, indicates that the precursor body was about 9 km in diameter. We conclude that the precursor of P/S-L 9 was of the order 9 km diameter and that the total impact energy will be of the order 10^8 megatons TNT.

Observations of comets discovered shortly after escape from jovicentric orbit, plus the discovery of P/S-L 9, indicate that the frequency of collision of objects orbiting Jupiter with the estimated impact energy of P/S-L 9 is of the order once per millenium [7]. Collisions with Jupiter of comets on free heliocentric orbits are several times more frequent. These collision rates are an order of magnitude higher than those predicted with the use of Opik's equations, which fail for very-low-velocity encounters with Jupiter.

The development of a train of cometary debris by tidal breakup leading to multiple impacts on a planet has direct relevance to the impact history of Earth. Both periodic and long-period Sun-grazing comets are subject to tidal disruption. A catastrophically disrupted periodic comet on a free heliocentric orbit can be expected to form a compact debris stream somewhat similar to but much narrower than an ordinary meteoroid stream. If such a stream intersects Earth's orbit at one of the nodes, Earth will be subject to repeated impacts as a result of its annual passage through the stream [8–10]. High-inclination periodic comets tend to be driven to Sun-grazing orbits [11], and the formation of compact debris streams should occur fairly frequently. Breakup of very large (several hundred kilometers in diameter) periodic comet nuclei should have occurred occasionally during the last 0.5 Ga, leading to comet showers with durations of the order of 10^5 yr. If one such breakup occurred when the distance to a node was near 1 AU, an intense pulse of bombardment lasting a few decades may have occurred. We postulate that just such an event happened at K/T boundary time.