surface cracks or extruded lobate-flow ridges are visible at this resolution on this flow front (nor on the "second" top-flow front 7 km southeast of *X*). The shadow pattern and ground texture 6 km N50°W of *B* suggest that this material at the lip of the flow is higher than that 2 km east of this lip.

Apex craters (*E* and *C*, Fig. 1) are visible on several conical hills on the edge and floor areas of the crater; these resemble pyroclastic cinder cones and are somewhat smaller than the major conical hills in central Copernicus, which are some 2100 m in height.

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Biologic Effects of Supernovae

Abstract. *Estimates of the probability that nearby explosions of supernovae have occurred during the earth's history and the biologic effects of the radiation therefrom are presented. They suggest that cosmic radiation from supernovae could have caused the extinction of many exposed animals without the simultaneous extinction of plant life. This suggests that supernovae should be considered as one possible mechanism by which fauna become extinct.*

Since supernovae are thought to be an important source of cosmic radiation (*1, 2*), one would expect that a nearby explosion would result in a significant increase in background radiation. One of the most obvious consequences of a large acute dose of cosmic radiation would be the mass extinction of organisms. It has been suggested by several investigators (*3–5*) that the explosion of supernovae might account for the mass extinction of fauna as observed in the geologic record.

Two independent groups (*1, 2*) arrived at a similar estimate for the energy released in the form of cosmic radiation during the explosion of supernovae. In addition, the frequency of nearby explosions can be calculated from the frequency of observed supernova remnants (*6, 7*) and the estimated distribution of supernovae in our galaxy (*6*). We have used these estimates to calculate the cosmic ray flux received here on earth following the explosion of nearby supernovae. This in turn has permitted us to ask several interesting questions, the most pertinent being whether the magnitude and frequency of the doses are plausible and of biologic interest.

Supernovae can be divided into two types (I and II) according to their optical characteristics, the general release of energy, and distribution in space. Supernovae of the first type are basically old stars of comparatively small mass ($\simeq$ 1 solar mass), which liberate 10^{48} to 10^{49} ergs upon explosion. Since they are less energetic and occur less frequently than type II supernovae, they are not considered in this report. Supernovae of the second type are massive young stars whose evolution is proceeding rapidly. As a result of detailed hydrodynamical calculations, Colgate and White (*2*) found that 2×10^{51} ergs are released in the form of cosmic rays ($E_{\rm cr}$) in the explosion of a large type II supernova (10 solar masses). On the basis of general considerations of the distribution of energy in the various modes (cosmic rays, magnetic field, kinetic energy), Ginzburg and Syrovatskii (*1*) arrived at a value close to 10^{51} ergs. We will use $E_{\rm cr} = 10^{51}$ ergs and $E_{\rm cr} = 10^{50}$ ergs, values which should approximate fairly accurately the upper and lower limits on $E_{\rm cr}$.

The cosmic ray flux at the top of the atmosphere, due to an explosion occurring a distance R light-years away, for $E_{\rm cr} = 10^{51}$ ergs is,

$$F = 9 \times 10^{13}/R^2 \text{ erg cm}^{-2} \qquad (1)$$

Since cosmic rays are charged particles, they will be affected by the interstellar magnetic field to some extent. However, for the nearby explosions that are of importance here this effect is negligible.

The normal cosmic ray flux at the top of the atmosphere is 9×10^4 erg cm^{-2} year^{-1}. It produces a dose of about 0.03 roentgen/yr (*8*), so the dose due to a supernova explosion R light-years away will be, for $E_{\rm cr} = 10^{51}$ ergs, approximately

$$D = 3 \times 10^7/R^2 \text{ roentgens} \qquad (2)$$

A very important factor is the time over which this dose occurs. Since diffusion effects can be neglected for relativistic particles traveling over comparatively short interstellar distances, such as are of interest here, the relevant time interval is that for the release of the energy in the form of cosmic rays. If the cosmic rays are produced by relativistic shock waves, as in the theory of Colgate and White (*2*), the time scale is of the order of 10^3 or 10^4 seconds, or less. In solar flares, relativistic protons are produced by plasma effects in a time of the order of 10^3 seconds. General considerations of the acceleration of particles by plasma turbulence (*9*) lead to the conclusion that the time scale is not too different from this during or soon after the explosion of a supernova. Therefore, it is safe to say that the dose D is received over a period of, at most, a few days.

From Eq. 2 it follows that R must be less than a few hundred light-years, if an appreciable dose is to result. Of the known supernova remnants, only CTS-1, at a distance of about 400 light-years, is anywhere near this close (*10*). However, it appears to be the remnant of type I outburst and would have a negligible effect. Of course, we have direct information only for events that have occurred in the past 100,000 years. For earlier times we must make estimates on the basis of the probability for the occurrency of a supernova within a distance of R_0 in t years. Type II supernovae are concentrated toward the galactic plane. Both theoretical and observational evidence indicate that their galactic distribution should be similar to that of the neutral hydrogen (*6*). According to Van Woerden (*11*) about 1 percent of the neutral hydrogen in the galaxy is in a disk with a radius of 3000 light-years and a height of 600 light-years centered on the sun. Hence, for R_0 less than 600 light-years the number of type II supernovae within R_0 in t years is

$$N(R\,R_0,\,t) = 2 \times 10^{-12} ftR_0^3 \qquad (3)$$

where f is the frequency of type II supernovae in the galaxy per year. It has been estimated from counts of supernova remnants in our galaxy (*6, 7*) that f is 0.02/yr, corresponding to one type II supernova in the galaxy every 50 years. Using Eqs. 2 and 3 one can easily compute the time needed for one dose greater than or equal to D_0.

Figure 1 shows that, even for the

Table 1. Probable number of doses of a given magnitude or greater received at earth in geologic time.

Age (millions of years)	Period or group	Probable number of doses of a given magnitude or greater * (roentgens)			
		200	500	1000	25,000
600	Precambrian	60	10	4	1
400	Amphibians†	40	8	2	0
300	Reptiles†	30	6	2	0
150	Mammals†	15	3	1	0

* Taken from Fig. 1, based on $E_{cr} = 10^{50}$. † Since their evolution.

lower limit $E_{cr} = 10^{50}$ ergs, the earth was probably exposed to an acute dose of 500 roentgens (r) every 50 million years and 1500 r every 300 millions years. For the upper limit on E_{cr}, the above doses would be a factor 10 higher.

In terms of the geologic record, Table 1 shows that in the 600 million years since Precambrian times it is probable that at least one supernova occurred producing a dose of 2500 r or more, four producing 1000 r or more, ten with 500 r or more. The probable number of doses are also listed for those periods following the evolution of amphibians, reptiles, and mammals. Again we emphasize that these values are for the lower limit $E_{cr} = 10^{50}$ ergs.

Although doses of this magnitude would result in a substantial increase in the mutation rate, the number of new mutations would still be negligible compared to the existing genetic variation and the number of spontaneous mutants that would arise in the intervening millennia. Consequently, a brief increase in the mutation rate would not create a state of macroevolution as has been suggested by some authors (*4*). Rather, the main biologic effect of supernovae, if any, would be the direct extinction of some species by radiation. The genetic consequence of such a crisis might be the exploitation of the newly created environments and vacated niches by the surviving species.

The paleontological record clearly shows the periodic mass extinction of large groups of animals as well as the more or less continuous extinction of different forms of life. This subject has been reviewed several times (*12, 13*) and more than one interesting hypothesis has been presented (*3–5, 12–15*). Apparently any theory of mass extinction must explain how the world's flora remained little affected by the crises that so dramatically affected many diverse groups of fauna. Another puzzling aspect is the observation that mass extinctions on land were at times accompanied by the mass extinction of marine organisms, including plankton. These observations are difficult, if not impossible, to reconcile with a single basic cause, and all the hypotheses presented have been criticized on one or more grounds. It is our contention that the explosion of supernovae should be considered as one possible mechanism by which fauna became extinct during geologic times.

The LD_{50} (lethal dose, 50 percent effective) for most laboratory animals is 200 to 700 r (*16*). In addition, most laboratory animals are rendered permanently sterile at these same doses (*17*). Consequently, a uniform dose of this or of higher magnitude would decimate, if not annihilate, many of the exposed land animals. However, even under these conditions, it could be expected that some animals would survive while others would perish because of differences in exposure and to extreme variation in radioresistance. For example, female mice are almost completely and permanently sterilized by 80 r (*17*), while many thousands of roentgens are required to kill insects and single-celled organisms.

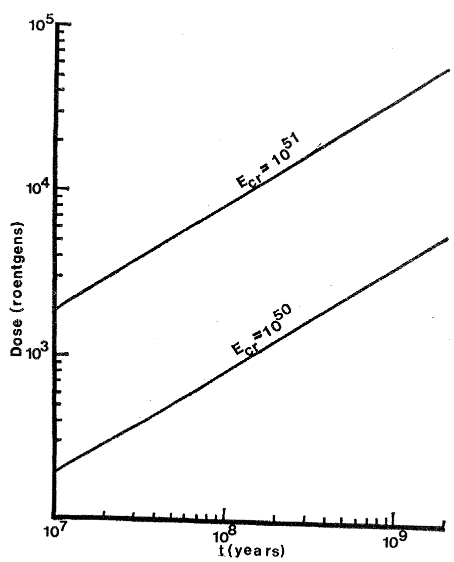

Fig. 1. Time *t* in years between supernova outbursts that deliver a dose of *D* roentgens or more for 10^{50} and 10^{51} ergs of cosmic radiation (E_{cr}) from exploding supernovae.

The highest single dose estimated for the period of time since the evolution of reptiles is at least 1000 r and possibly as much as 10,000 r (Table 1). In addition the table shows that several doses of lower magnitude probably occurred that could have adversely affected the more sensitive, exposed fauna.

It should be emphasized that the calculations are only estimates. In this respect it seems likely that the doses based on an E_{cr} of 10^{51} ergs are too high or that the estimated frequency of supernovae is too high. Thus it is unlikely that the earth has been subjected to 2000 r every 10 million years, since there is no evidence for the worldwide extinction of organisms in recent geologic times. However, the calculations based on the slightly lower limit of 10^{50} ergs leads to the figure of one dose of 500 r or more every 50 million years. Thus, the calculated doses are close to a range that would be plausible and also have a dramatic effect on the earth's fauna.

Available data indicate that plants would have been affected far less than animals by an acute dose of a few thousand roentgens or less. The large majority of those plants tested by Sparrow and Sparrow (*18*) had an acute lethal dose of well over 2000 r. Doses predicted by Taylor (*19*) to produce severe inhibition of growth of deciduous and coniferous species were 3000 to 7000 r and 500 to 800 r, respectively. Even more important than resistance of plants to radiation would be their ability to recover in the ensuing thousands of years by asexual propagation and especially by repopulation of species by seeds and spores that are very radioresistant. For example, the $LD_{50/15}$ for the seeds of agricultural plants varies from 10,000 r to greater than 50,000 r (*20*). It is obvious, though, that many plants would be severely damaged by an acute dose of 500 r or greater, particularly the present-day coniferous species. This disruption in the biologic community could temporarily destroy the normal habitat and food chain of many animals. Thus, it is not unlikely that some animals would perish because of the indirect effects of radiation on living organisms. These considerations suggest that doses in the range of 500 r could have severely decimated many animal populations directly or indirectly, whereas the affected plants could have ultimately survived through their radioresistant seeds and spores. Furthermore, if the biologic community were seriously disrupted it could allow the proliferation and radiation of animal and plant species that were able to take advantage of the change in the environment. The pattern of biologic evolution following radiation has recently been discussed in detail by Woodwell (*21*).

It was Schindewolf's position that high-energy radiaton might penetrate to depths sufficient to cause the extinction of marine organisms, either directly or by means of secondary effects, such as the formation of radioactive isotopes. More recently, Loeblich and Tappan (*4*) have suggested that the mass extinction of planktonic organisms at the close of the Permian period might conform to a pattern expected of cosmic radiation. The intensity of the ionizing component of cosmic radiation in water varies with depth according to

$$J_x = J_0 (1 + 0.1x)^{-2.1} \qquad (4)$$

where x is the depth in meters. A dose of 1000 r would yield only 72 r after penetrating 25 m of water. A dose of 5000 r would be reduced to 116 r after penetrating 50 m. Thus, most planktonic life (both plant and animal) would be protected since they occur at greater depths. Also, fish and other marine animals found at depths greater than 25 to 50 m would be protected against doses as great as 5000 r. However, it is obvious that those marine organisms living in shallow water would be vulnerable. In particular this group might include amphibians and some marine reptiles.

As for the secondary effect of the radioactive decay of isotopes produced by cosmic rays, our estimates show that such effects are of little significance if one assumes doses in the range estimated.

The above considerations suggest that cosmic radiation from exploding supernovae could have caused the extinction of many exposed animals, including some marine organisms, without the simultaneous extinction of plant life. This is an attractive finding since it conforms to one of the most puzzling aspects of mass extinction. It is also interesting that mass extinctions have occurred approximately once every 60 million years since Cambrian times. Our estimates show that a dose of at least 50 r should occur once every 50 million years. However, radiation from supernova explosions cannot account for the extinction of small marine organisms (protozoans and algae), at least for the doses estimated in this study.

While it is true that the parameters involved in making these calculations are poorly known, it is perhaps more than coincidental that the estimates of these parameters should lead to calculated doses that are roughly necessary to produce some of the patterns of mass extinction observed in the geologic record.

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Ammonium Ion Concentration in the Primitive Ocean

Abstract. *If ion exchange on clay minerals regulated the cations in the primitive ocean as it does in the present ocean, the* pH *would have been 8 and the* K^+ *concentration 0.01*M. *Since* NH_4^+ *and* K^+ *are similar in their clay-mineral equilibria, the maximum* NH_4^+ *concentration in the primitive ocean would also have been 0.01*M. *An estimate of the minimum* NH_4^+ *concentration is* 1×10^{-3}M, *based on the reversible deamination of aspartic acid and the assumption that aspartic acid is necessary for the origin of life. The rate of this nonenzymic deamination is rapid on the geological time scale.*

Although the presence of NH_3 is considered important in the synthesis of organic compounds on the primitive Earth (*1*), there have been no quantitative estimates of the concentrations based on the organic chemistry or on detailed atmospheric models (*2*). The stable species of nitrogen would have been ammonia under the generally accepted reducing conditions, but most of this NH_3 would have dissolved in the ocean to form a mixture of NH_4^+ and NH_3, the ratio depending on the *p*H. The available nitrogen places one upper limit on the NH_4^+ concentration. If all the nitrogen in the atmosphere (755 g/cm^2) were placed in the present ocean (282 liter/cm^2) as NH_4^+, the concentration would be 0.19*M*. If the primitive ocean were smaller or the nitrogen in the rocks is included, the concentration would be correspondingly higher.

This upper limit would be reduced by the clay minerals. The *p*H and the cations in the present ocean are regulated largely by the clay minerals, as was first suggested by Sillén (*3*) and discussed by others (*4, 5*). This regulation is based on the fact that the ion-exchange capacity of the oceanic sediments is large compared to the H^+ and the buffer capacity of the ocean. The ion-exchange capacity also appears to be sufficient to regulate the concentrations of Na^+, K^+, Ca^{++}, and Mg^{++}. The ion-exchange equilibrium between H^+ and K^+, as well as the other cations, controls the *p*H of the oceans at 8.1.

We can expect that a similar regulation of cations took place in the primitive ocean as long as there was a