matters arising

Biotic extinctions by solar flares

REID *et al.*[1] have suggested a mechanism by which solar protons might catastrophically deplete atmospheric ozone during a reversal of the Earth's geomagnetic field, when its shielding effect is weakened. Organisms would thereby be exposed to a harsher ultraviolet environment, producing extinctions, such as those Hays[2] observed, closely correlated with geomagnetic reversals in deep-sea sediment cores. They further suggest that mass extinctions, such as those which took place at the close of the Cretaceous, may have thus occurred. Reid *et al.* assume that during a reversal the geomagnetic field effectively disappears for ~ 1,000 yr. They also assume that solar flares sufficiently intense to cause extinctions occur at intervals of ~ 1,000 yr or more. We propose to examine the validity of these assumptions by comparing them with geomagnetic reversals identified by Tarling and Mitchell[3] for the past 75 Myr, and small scale (radiolarian) and large scale (dinosaurian) extinctions.

Hays[2] found four radiolarian cases of extinction (involving 6 species) during the past 2.5 Myr, in which time 10 geomagnetic reversals occurred[3]. According to the model proposed by Reid *et al.*, the expected number of extinction events (E) is related to the probability of occurrence of a strong solar flare during any year (P_s) and the number of successive years during which the magnetic field is effectively absent (T) as

$$E = RTP_s \qquad (1)$$

where R is the number of reversals during the period considered. Solving for P_s, and substituting the values cited above:

$$P_s = E/RT = 4\times 10^{-4}\ \text{yr}^{-1} \qquad (2)$$

The value for P_s is lower than assumed by Reid *et al.* Given their estimate of $P_s = 10^{-3}\ \text{yr}^{-1}$, to satisfy equation (1), the magnetic field would have to disappear for 400 yr during a reversal, an interval shorter than the generally accepted value[4]. A reduction in P_s would not, in our view, impair the utility of the model proposed by Reid *et al.* in producing periods of small scale extinction.

It is, however, evident that the terminal Cretaceous (dinosaurian) extinctions affected a much broader range of organisms[1,5] than the radiolarian ones described by Hays. The extinction of the dinosaurs occurred within a short but undefined interval ~ 18 Myr after the end of a lengthy period of normal polarity[6,7]. During these 18 Myr, eleven reversals took place[6], but the diversity of terrestrial and marine reptiles remained constant up to the end of the Cretaceous[8].

A solar flare powerful enough to produce such extinctions would, therefore, have been much more powerful than any directly considered by Reid *et al.* Because no extinction as severe as those in which the dinosaurs were eliminated have subsequently taken place (or $E = 1$), and at least 197 reversals have since occurred ($R = 197$; set $T = 10^3$ yr), then the frequency of a hypothetical giant flare according to equation (2) is

$$P_s = (1.97\times 10^5\ \text{yr})^{-1}$$

or ~ 1 per 200,000 yr. Solar proton events have been studied only during the past 15–20 yr (ref. 1), and there is little hard evidence for the existence of giant flares, although instabilities in solar activity are now receiving more attention than formerly[9]. We therefore concur that the supernova model, as proposed by Terry and Tucker[10] and Ruderman[11] remains worthy of consideration. Although the coincidence of a reversal and the terminal Cretaceous extinctions would invalidate neither model, Keating[12] notes that this coincidence has not been demonstrated.

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CRUTZEN AND REID REPLY—We certainly agree with the interesting remarks of Béland and Russell[1]. Our model was primarily intended to provide a tentative explanation for the apparent mysterious association between geomagnetic polarity reversals and small scale extinctions, as documented by Hays[2]. The relationship between polarity reversals and mass extinctions, such as that at the close of the Cretaceous, is not well established, and our mechanism is only a possible candidate.

In terms of ionising radiation, the solar flares of August 1972 dissipated $\sim 6\times 10^5\ \text{erg cm}^{-2}$ in the polar stratosphere. A similar flux of energy over the entire projected area of the Earth would be caused by the γ-ray 'pulse' ($\sim 10^{49}$ erg (ref. 3)) from a supernova 1,000 light yr away, while a supernova 30 light yr away would create a flux 1,000 times larger. It is not likely that the Sun could produce such a colossal flare, but several supernovae may have occurred within a distance of 30 light yr during the lifetime of the Solar System[4].

Although the shielding of ultraviolet light by NO_2 must be considered, any ozone depletion caused by such supernovae would seriously affect the biosphere[5]. However, other consequences of the vast amounts of nitrogen fixed in the atmosphere are worth considering. Assuming maximum efficiency of NO production, the supernova would fix ~ 1,500 Mt of nitrogen, which is almost 10 times the presently estimated annual global nitrogen fixation rate[6]. This could perturb ecological systems. Furthermore, the column density of NO_x could initially reach unhealthy concentrations of 10^{19}–10^{20} molecules per cm² and although detailed calculations are necessary to confirm the idea, it may seem that there could be substantial production of NO_2 and even O_3 by the reaction $2NO + O_2 \rightarrow 2NO_2$. Given absorption cross sections of $NO_2 > 10^{-19}\ \text{cm}^2$ at wave lengths $\lesssim$ 650 nm, severe perturbations in photosynthesis rates and in the radiation balance of the Earth may result.

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