not favour a direct land connection of Africa with Europe at that time[2].

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Cometary showers and unseen solar companions

THE existence of an unseen solar companion has occasionally been invoked to account for some unsolved astrophysical problem. The latest hypothesis, as proposed by Whitmire and Jackson[1] and by Davis *et al.*[2], is that such a companion, in a distant eccentric orbit, periodically passes through the Oort cometary cloud and causes a shower of comets from an also unseen inner Oort cloud reservoir. Impacts on the Earth from these repeated showers then results in periodic biological extinction events.

A shower of comets from the inner Oort cloud is expected to involve some 2×10^9 comets passing four times each within the orbit of the Earth, over a period of $\sim10^6$ yr. This episodic flux is equivalent to the presently estimated steady-state cometary flux of 16 comets $\text{AU}^{-1}\,\text{yr}^{-1}$ (ref. 3) (brighter than $H_{10}=11$) for a period of 500 Myr. Thus, the seven to nine cometary showers, spaced at 28-Myr intervals, for which a cratering record has allegedly been found[4], would produce as many craters as the steady-state cometary flux over the Solar System's entire history.

Present estimates of the cratering rates on the Earth and Moon based on dated surfaces of very different ages[5], are in agreement with one another, after allowing for differences in gravity-scaling and impact cross-section. Estimates of the expected cratering from Earth-crossing asteroids are roughly twice these values[6]; estimates of the cratering from comets range between 0.3 and 1.0 times the rate based on dated crater surfaces[7,8]. Although it seems that the known Earth-crossing objects yield a total cratering rate on the Earth and Moon which is too high, the problem is not serious because of the large error bars in these calculations.

However, adding the flux predicted for cometary showers every 28 Myr makes the problem significantly worse. These showers result in an 18-fold increase in the mean cometary flux over the past 400 Myr, resulting in between 5.4 and 18 times as many additional craters on the Earth and Moon in that period, outside any reasonable error limits on these rates.

Even allowing this discrepancy, the probability that such a cometary shower would result in the impact of a 10-km diameter cometary nucleus on the Earth is about 0.055 per shower. Thus, major events like the Cretaceous–Tertiary (K–T) extinction might be expected on average every 510 Myr, considerably longer than is observed.

One can also consider the stability of the hypothesized 'death star' orbit. With a perihelion of 3×10^4 AU and a period of 28 Myr, the proposed companion star would have an aphelion of 1.54×10^5 AU. Monte Carlo simulation modelling of the dynamical evolution of a large sample of hypothetical stars starting with that orbit[9] has shown that 23% escape the Solar System in 10 orbits or less, and 86% escape in $<10^9$ yr. The average change in orbital period per orbit is 10%. Thus, it is unlikely that an unseen companion star could have remained in a constant period orbit, over the period suggested by the terrestrial extinction record, and impossible that it has been in that orbit since the origin of the Solar System.

If a more tightly bound original orbit were to be assumed, the problem of the increase in the terrestrial cratering record would only worsen because of the increased frequency of cometary showers implied. Also, the Oort cloud population would have been severely depleted by the repeated perturbations of the companion star, implying an immense initial cloud mass. If, on the other hand, one assumed that the companion star had been recently captured, an event with a probability of 10^{-13}, we would still expect an approximate doubling of the cometary cratering on the Earth in the past 300 Myr.

Finally, an additional problem with the death star scenario is that there do not seem to be many random events mixed with the periodic signal from cometary showers. Random Apollo asteroid impacts should produce a major extinction every 10^8 yr or so, and large (though not necessarily catastrophic) cometary impacts should occur with about one-third that frequency.

The proposed death star scenario, however interesting, has consequences which its proposers have failed to consider, and for which we have little evidence. If the periodicity in the fossil extinction record is indeed real, then some other mechanism must be found for creating it. It would seem wise to look for a period of which we are already aware, for example, the time between the Sun's galactic plane crossings is close to the required value, though the extinction mechanism remains a mystery. Even so, this would seem a more worthwhile avenue for future study than continuing to chase an invisible star which does not exist.

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MULLER *ET AL. REPLY*—Weissman's objections are based, we believe, on a misunderstanding of the companion star model[1,2] and a misinterpretation of the periodicity discovered in the crater data[3]. We will review the salient features of these before addressing Weissman's points directly.

In the companion star model, the Sun's companion has an orbit with a 26-Myr period, matching that seen in the mass extinctions[4]. During perihelion, it passes close enough to the Oort cloud of comets to precipitate a shower in the normally depleted 'loss cone' region swept clean by Jupiter and Saturn; this requires the companion's orbit to have an eccentricity greater than ~0.6. The number of comets in the shower depends on the number in the inner part of the Oort cloud, but this number is not known within a factor of 10. If we take the nominal value of 10^{13} from the extrapolation of Hills[5], we find the number of comets in a shower to be 2×10^9 and the number of impacts per shower to be 25; but these numbers could be as small as 4×10^8 and 5, respectively.

As stated in our original paper[1], and subsequently checked with detailed calculations[6], the orbit we postulate is stable, with a half life of $\sim10^9$ yr, not long enough for the companion star to have been in such a large orbit at the formation of the Solar System. As it is extremely unlikely that a star could have been captured by the Sun, the most likely scenario has the companion in a relatively tight orbit 5×10^9 yr ago, with perturbations from passing stars and molecular clouds over 5×10^9 yr expanding the orbit to the present one.

In Grieve's survey of impact craters on the Earth[7], there are 58 craters with ages <250 Myr, but only 29 of these have uncertainties in their ages of 20 Myr or less, and only 13 of these remain when we exclude the very recent (<5 Myr old) craters; these appear in a table in our paper[3]. Our analysis of these craters showed a statistically significant periodicity, with period and phase identical