Comets, Ice Ages, and Ecological Catastrophes[1]

(Letter to the Editor)

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[1]First discussion of comets causing ecodisaters such as the extinction of the dinosaurs 65My ago; initially issued as a Cardiff Astrophysics Preprint, a Kellog Preprint and later published in *Astrophys.Sp.Sci.*, 53, 523-526 (1978)

Abstract

A total mass $\sim 10^{14}$ g added to the Earth's upper atmosphere in the form of small particles of high albedo for visual wavelengths would produce an inverse greenhouse effect, shielding ground level from sunlight but permitting infrared radiation from the ground to escape into space. Such a mass of small particles might be acquired by the Earth in a close approach to a cometary nucleus. Ice ages and ecodisasters, such as that which occurred 6.5×10^7 years ago, could arise from the effects of such an addition of small particles.

Interstellar grains have a significantly higher extinction for optical wavelengths than they have in the infrared. The optical scattering by dielectric particles, often referred to as 'silicates' but which may also contain polysaccharides (Hoyle and Wickramasinghe, 1977a,b). The infrared opacity. on the other hand, is mainly due to true absorption. For homogeneous silicate particles with sizes $\sim 10^{-5}$ cm, the opacity at optical wavelengths is $\sim 3 \times 10^4$ cm^2 g^{-1}. However, for porous silicate particles of the type found in micrometeorites, or particles composed of needle-shaped cellulose chains of length $\sim 10^{-5}$ cm the optical opacity is $\sim 3 \times 10^5$ cm^2 g^{-1} , much higher than the value $\sim 3 \times 10^3$ cm^{2}g^{-1} that is appropriate in the infrared.

A layer of small dielectric grains with a surface mass density of $\sim 10^{-5}$ g cm^{-2} would give an optical depth of order unity in the visual. Such a layer in the Earth's upper atmosphere would evidently give a very high visual albedo for our planet. It would largely prevent sunlight from penetrating to ground level. On the other hand, it would not prevent infrared radiation (coming from below) escaping into space. Such a layer would therefore produce a marked cooling at ground level, and it would cut down the supply of solar radiation from terrestrial photosynthetic plants and organisms. The total mass in such a layer would be $\sim 5 \times 10^{13}$ g, comparable to the mass emission from a typical comet with perihelion passage < 1 AU. Particularly brilliant comets may indeed eject up to $\sim 10^{15}$g, of which an appreciable fraction could be in grains. It is evidently important then to consider the possibility that the Earth might on rare occasions pick up a significant quantity of cometary grains, since if this were to happen there could be a serious perturbation both of climate and of the terrestrial ecosystem.

To fix ideas we shall assume that a dense inner halo of grains surrounds the cometary nucleus, the inner coma having dimensions of $\sim 10^9$ cm. On this view the inner halo is a reservoir with an input of grains through evaporation from the nucleus, and with a loss of grains into a larger coma and thence to the dust tail of the comet. We take penetration of the inner coma to be a necessary condition for the Earth to pick up a significant quantity of grains - that is to say, the Earth must come to within 10^9 cm of the nucleus of a comet, a near-miss from a direct collision.

There are of the order of 5 comets per year that come to a heliocentric distance ~ 1 AU, and therefore of the order of 10 crossings per year of a heliocentric sphere with radius 1 AU. Such a sphere has a surface area of 2.8×10^{27} cm^2. The chance of the Earth coming within 10^9 cm of a cometary nucleus which crosses the sphere at random is therefore ~ $\pi (10^9)2/2.8 \times 10^{27}$, and for ~ 10 random crossings per year the chance of a major 'dust-acquiring' encounter is ~ 10^{-8} per year. The possibility of a direct hit on a cometary nucleus would be of the same order. Although more dramatic and seemingly more devastating, a direct hit would not necessarily be as far-reaching in its effects as the addition of ~ 10^{14} g of small grains of high visual albedo would be.

Small grains incident on the Earth are slowed gently by the terrestrial atmosphere and are not subject to evaporation, as larger grains are. A layer of such grains in the stratosphere with optical depth > ~3 in the visual, but with optical depth << 1 in the infrared, would quickly disrupt the food chains of large land and sea animals. Photosynthesis by phytoplankton would fall to a low rate. Leaves would soon wither from trees, leading to the extinction of large browsing animals - extinction probably within months.

Eventually there would be a worldwide fall of temperature, but the timescale for cooling would be about ten times longer than the ~ 1 year required for an eco-catastrophe to take place. For a mean oceanic temperature of 15°C, say, it would be possible to draw on ~ 5×10^{32} erg from the oceanic heat reservoir before a steep temperature fall set in, and such a reservoir is equivalent to ~10 year supply of sunlight. Cooling water at the sea surface would sink, stirring the sea until the mean temperature of the water fell to 4° C, after which the sea surface would quickly freeze, and the oceanic heat reservoir would then be gone. Before freezing, however, evaporation at a rate of several metres of water per year would take place, and water vapour from the sea would be carried by winds to the land areas. The land areas would be cold enough to induce heavy precipitation, thereby transferring the latent heat of condensation of the water to these areas. In the first year or two this transfer of latent heat from the oceans to the land could well be sufficient to keep some rivers and freshwater lakes unfrozen, but thereafter freezing would occur everywhere over the land. If an appreciable fraction of the oceanic heat reservoir were used in the evaporation of water vapour, and if an appreciable proportion of the water vapour were carried to the polar regions, the average depth of ice added there each year might well be as much as 100 ft. Over ~ 10 years, the timescale of oceanic evaporation, the average depth of ice built up on the Earth's polar and high temperate zones would be ~ 1000 ft, with still greater depths being deposited on mountains.

We distinguish several possibilities:

(1) *Optical depth (visual) >~ 3, timescale ~1 year*. The expected outcome in this case would seem to correspond closely to the post-Cretaceous ecodisaster of 6.5×10^7 years ago, with its well-known extinction of the dinosaurs, and indeed of all animals with body weights above about 25 kg (K-TEC, 1976). The timescale is short enough for extensive glaciation of the land to be avoided. With rivers continuing to run, and with some lakes remaining unfrozen, fresh-water organisms would survive - their food chains, depending on decaying vegetable matter, would take longer to disrupt than those marine organisms that were dependent on phytoplankton. The seeds and nuts of land plants would survive,

and small animals living on seeds and nuts would also survive.

(2) *Optical depth (visual) > ~ 3, timescale > ~ 10 years*. An ecocatastrophe followed by worldwide glaciation and freeze-up ensues, with widespread extinctions of marine and fresh-water organisms. Land plants could eventually regrow from seeds, however, once the covering cloud of refractive particles had fallen to the ground.

(3) *Optical depth (visual) ~ 1, timescale ~ 1 year*. There would be a considerable ecological perturbation, resulting perhaps in some extinctions; but with the short-term situation corresponding more to a grey-out than a black-out there would be neither a major ecodisaster nor a worldwide glaciation.

(4) *Optical depth (visual) ~ 1, timescale >~ 10 year.* A grey-out arctic situation would develop, with great glaciers being deposited on the land. An ecological disruption rather than a catastrophe, with survival probable for most species. An ice age.

Ultraviolet light from the Sun incident on a cloud of small panicle in the upper atmosphere must induce charges on the particles, which would then be subject to the electrical fields that arise in geomagnetic storms. We are informed (L.C. Hale, private communication) that the vertical components of such fields play an important role in controlling the downward drift of small particles in the upper atmosphere. Thus the time for which a cometary cloud of small particles would persist could well be related to the interaction of the solar wind with the Earth's magnetic field. Timescales for downward drift could therefore be considerably variable, perhaps being much extended during epochs of geomagnetic reversal. The severest effects of dust layers in the upper atmosphere could thus be correlated with geomagnetic phenomena, suggesting a possible relation to the radiolarian extinctions of the last 2.5 million years reported by Hays (1971).

The present discussion of ice ages, taken with the probability of ~ 10^{-8} yr^{-1} estimated above for a major dust-acquiring cometary encounter, implies an interval of ~ 10^{8} years between ice epochs. While this estimate is in satisfactory correspondence with the broad geological record, it does not in itself explain the several glaciations of the recent Pleistocene epoch. Why should several such en- counters have been compressed within the last 10^{6} years? The probability 10^{-8} yr^{-1} was calculated for cometary orbits of random elements, and for an absence of correlation between one comet orbit and another. Correlated families of orbits with small inclinations or with perihelion distances close to 1AU would produce a bunching in time of dust-acquiring encounters. Such correlations could arise from the perturbation of the Oort comet cloud by a particular star, possibly aided by further perturbations from the major planets.

We end by mentioning an objection to 'small cause' theories of the incidence of ice ages. Such theories proceed on the assumption that initially small effects can grow into large effects through positive feedback. A little deposition of ice on the land cools the surrounding air a bit, increases the local albedo a bit, leading to a little more ice being deposited - and so on to bigger things. If this were true, it is hard to see how the Earth, once locked into a fully grown ice age, could ever escape from it, except possibly through an exceedingly long-term change in the disposition of land and sea areas. The evidence, however, is to the contrary. Fully blown ice ages can vanish with remarkable speed, in ~ 10^3 years, which is readily understandable from the present viewpoint. The onset of an ice age is due to an essentially instantaneous very large perturbation of the terrestrial climate that deposits extensive sheets of ice on the land. After the perturbation, recovery to the former climate is impeded by the self-sustaining properties of the ice fields, by their marked cooling of surrounding air, and by their high visual albedo. Nevertheless, there is a slow trend toward re-establishing the former climate, since once the ice begins to melt both local cooling and reflectivity are progressively reduced. This positive feedback exponentiates the melting rate, leading in the end to a rapid disappearance of the ice fields.

References

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