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AUTHOR(S) Jack G. Hills, T-6

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Invited Review Talk
COMET SHOWERS AND NEMESIS, THE DEATH STAR

Jack G. Hills
Theoretical Division
Los Alamos National Laboratory
Los Alamos, NM 87545

Today, I would like to discuss the recently proposed hypothesis that the observed periodic extinctions of terrestrial species is the result of comet showers catalyzed by a hypothetical distant solar companion, Nemesis. This is a tale of global death by comet bombardment of the earth.

Before I discuss the Nemesis hypothesis, I shall first review the observed evidence for periodic extinctions in the fossil record and the evidence that some of these extinctions result from astronomical impacts.

I. Mass Extinctions and Astronomical Impacts

The two most severe of the past three mass extinctions have been attributed to impacts of large asteroids or comets. The oldest, and most severe of these three extinctions was produced by the Cretaceous-Tertiary impactor of 65 million years ago. It caused a clay layer an inch thick to be deposited around the entire earth.

From the amount of iridium and platinum in the clay layer, Alvarez et al. (1980) estimated the diameter of the C-T Impactor to be about 10 km if it were a typical earth-crossing asteroid with a composition similar to that of a carbonaceous chondrite. This composition is characteristic of undifferentiated material in the Solar Nebula. It is orders of magnitude richer in platinum and iridium than the crust of the earth which is severely depleted as the result of these siderophile elements having settled to the iron core. An earth crossing asteroid having a typical impact velocity of 20 km/s would produce an impact energy of 10^8 megatons or more than 10^4 times the combined energy of all nuclear weapons on earth.

The C-T impactor could also have been a comet. Comets are largely ice with a mixture of 10-50% solid undifferentiated material, so the required comet would have to be 2-10 times as massive as an asteroid in order to lay down the same amount of platinum and iridium. At a typical velocity of 60 km/s, the impact energy would be about 10^9 to 10^{10} megatons or about 10^5 to 10^6 times larger than the world's nuclear arsenal.

The next most severe of the past three mass extinctions was the Eocene-Oligocene Extinction of 30-35 million years ago. Alvarez, W., et al. (1982) find three different groups of tektites associated with this extinction indicating that at least three separate large impact events occurred during this extinction. Tektites are glass beads produced by the rapid cooling of molten rock which jets from the point of impact of a meteorite with solid rock. Such beads are also responsible for the rays around lunar impact craters. The multiple impacts associated with this particular mass extinction are consistent with the comet shower impacts predicted by the Nemesis hypothesis.

The latest mass extinction was 15 million years ago. There is no evidence of an asteroid-comet impact associated with this extinction. However, according to the paleontological data of Raup and Sepkowski (1984), this is the least severe of the past three mass extinctions. It produced the death of only 20% of all the families of species in the ocean. The Cretacious-Tertiary extinction eliminated more than 70% of such families in addition to killing off the dinosaurs and many other land species. The Eocene-Oligocene extinction eliminated about 50% of the ocean families. The Cretaceous-Tertiary and the Eocene-Oligocene Extinctions were the most severe ones of the past 200 million years. Only the two Late Permian mass extinctions that occurred between 200 and 250 million years ago were as severe.

It is perhaps not surprising that only the C-T and E-O Extinctions show clear-cut evidence of astronomical impacts. The remaining extinctions of the past 200 million years were much less severe, so the environmental stress may have been much less which suggests much smaller impactors which would have left behind less physical evidence. The two great extinctions of Late Permian are the most promising ones to search for additional evidence of mass extinctions, but the great age of these extinctions may make it difficult.

A. How An Impact Kills

How does the impact of an asteroid or comet actually lead to mass extinctions? The scenario is a long one: The impact produces a massive, dusty fireball which breaks out of the atmosphere. The fireball gas spreads out over the top of the atmosphere to produce a new outer atmosphere of hot gas and dust overlaying the old layer. The dust in the gas blocks out the sunlight which kills plants. The animals which feed on the plants starve or suffer severe thermal stress. I shall now discuss this scenario in more detail.

In addition to producing a crater, the impact produces a large amount of hot gas by the evaporation of much of the meteorite and some of the ground it impacts. The hot gas expands adiabatically and becomes less dense than the surrounding atmosphere. The resulting buoyancy causes it to rise through the atmosphere. It has become a classical fireball. Fireballs are not only produced by the explosion of nuclear weapons in the atmosphere, but they are also produced by large volcanic eruptions such as Mount St. Helens' which deposited 7 megatons into the atmosphere out of a total energy release of 36 megatons (Jones and Kodis 1982). They are also produced by large meteor impacts. For example, the Tunguska event of 1908 produced a fireball with an energy of 10 megatons. This "pillar of fire" was seen for 450 kilometers around the point of impact.

The rise of a fireball in the atmosphere produces a suction which entraps dust in the fireball. Fireballs are always dusty. The greater the energy of a fireball, the higher it rises in the atmosphere before its rise is stopped by its coming to pressure equilibrium with its surroundings. The largest man-made fireball was the 58 megaton Russian nuclear explosion of 1960. This was confined by the atmosphere. If fireball energy exceeds about 150 megatons, it never reaches pressure equilibrium in the atmosphere. Initially it slows down as it rises in the atmosphere. Finally, its radius begins to greatly exceed the local scale height and it begins to be accelerated upward by the pressure gradient in the atmosphere.

Colgate (1984) shows that this hot gas with the entrapped dust then floats to the top of the atmosphere where it spreads out to form a hot layer of gas over the entire atmosphere of the earth. This spreads out on a dynamical time scale, i.e., at the speed of a satellite in a low earth orbit. An observer on the earth would see a dark cloud pass over his sky at the speed of a low satellite. In less than 90 minutes the entire earth is enveloped in darkness. The optical depth through the inch of dirt associated with the C-T impactor is several hundred so the darkness is quite complete. The settling time of the dust is about a year.

The long period of darkness kills many species. This is especially true of those in the ocean because their normally beneign environment makes them less resiliant to changing conditions than land plants and animals. The drop in temperature associated with cutting off the sunlight will also be harmful to many plants and animals. After several months the temperature will begin to rise because what heat does reach the surface of the earth escapes with great difficulty; greenhouse heating occurs. Eventually the earth becomes warmer than it was before the mishap. Finally, the temperature returns to normal as the atmosphere clears.

B. Evidence for Periodic Extinctions

Raup and Sepkowski (1984) find evidence in the Paleontological Record that the mass extinctions on the earth over the past 250 million years are periodic with a period of 26 million years with the latest extinction occurring 15 million years ago. The greatest extinction killed about 96% of all ocean families while the average extinction killed about 75% of these families. These extinctions were not minor perturbations.

Alvarez and Muller (1984) have examined the times of impact of the major craters on the earth. They find that these cratering events are periodic with a period of 28.4 million years, and that the previous major cratering occurred 13 (± 2) million years ago. Both the period and the phasing are consistent with the observed mass extinctions on the earth. When there were major cratering events there were mass extinctions on the earth.

The craters have been attributed to comet showers produced by either a companion of the sun or to the passage of the sun through the Galactic Disk

II. The Nemesis Hypothesis

This hypothesis was proposed independently by Whitmire and Jackson (1984) and by Davis, Hut, and Muller (1984). In this hypothesis the sun has companion with an orbital period of 26 million years which requires the companion to have an orbital semimajor axis of 9 x 10^4A.U.

In this hypothesis, Nemesis activates a shower of comet as it passes inside the steady-state or Oort comet cloud.

I shall now discuss the Oort comet cloud and the reason for comet showers.

A. The Oort Cloud and Comet Showers

The Oort comet cloud, which forms a spherical shell extending from 20,000 to 200,000 A.U. from the sun, was found empirically by Oort (1950) from the known orbits of long-period comets. The tidal field of the Galaxy determines the outer boundary of this cloud.

Hills (1981) showed that the apparent inner boundary is a selection effect which results from the infrequency of the close stellar encounters needed to perturb comets within this zone into orbits which pass through the planetary system. Comets which cross the orbit of Jupiter suffer a perturbation which is about 10 times larger than their orbital binding energy. Half these comets are sent into hyperbolic orbits while the other half are sent into very much more tightly bound orbits of very short orbital period. These short-period comets cross Jupiter's orbit at each perihelion passage which results in further changes in their orbits. They are ejected into a hyperbolic orbit on a time scale which is short compared to their original orbital periods in the Oort cloud. Without perturbations by passing stars, all long-period comets in orbits which pass within the orbit of Jupiter would be kicked into hyperbolic orbits in one orbital orbit. We would not know that these comets existed.

Passing stars tend to produce an isotropic distribution of velocities in the comet cloud. If passing stars do not come by frequently enough, an observer in the comet cloud would see an isotropic distribution of velocities in all directions except for a cone of velocity vectors centered on the sun which correspond to comets in orbits which cross that of Jupiter. These comets are lost within one orbital period. This is the situation for comets with semimajor axes less than 20,000 A.U. For comets with semimajor axes larger than 20,000 A.U. passing stars with perturbations large enough to fill the loss cone come by the sun frequently enough so loss cones of these comets are always filled. There is a steady-state stream of these comets entering the planetary system. These comets constitute the classical Oort cloud.

When a star does pass inside the Oort cloud, it fills the loss cones of the comets in the inner cloud and causes a shower of these comets to enter the planetary system. This shower then lasts for the length of time needed for the comets in the shower to make one orbital period. These showers are not frequent. As an example, only 9% of the time will comets with semimajor axes less than 10,000 A.U. enter the planetary system in intense showers. Hills (1981) estimates that comets with semimajor axes less than 3000 A.U. would have their loss cones filled by passing stars about every 5 × 10^8 years. The resulting comet shower will last about 200,000 years and result in about 10-100 comets hitting the earth. Hills (1981) suggested that the C-T impact event might be the product of a comet shower caused by the random close passage of a star.

B. Perturbations by Nemesis

The Nemesis hypothesis proposes that the sun has a black dwarf or stellar companion with an orbital period of 26 Myrs. This object would have a semimajor axis of 90,000 A.U. which places it in the classical Oort comet cloud. While it perturbs the comets in the classical Oort cloud and tends to fill the loss cones of these objects, this effect is not noticeable as unbound stars in the solar neighborhood pass by often enough to keep the loss cones of these comets filled without the help of Nemesis.

If its orbit is sufficiently eccentric, Nemesis passes inside the Oort cloud at each periastron passage. If Nemesis is also massive enough, it fills the loss cone of the comets in the inner cloud which in turn causes a shower of these comets to enter the planetary system.

C. Mass and Eccentricity of the Orbit of Nemesis

I have recently used computer simulations to estimate the minimum mass of Nemesis and the minimum eccentricity of its orbit needed to produce the death showers suggested by the Nemesis hypothesis (Hills 1984). I have assumed that to produce the needed death showers it is necessary to fill the loss cones of comets with semimajor axes less than 4000 A.U. Column 1 of Table I shows the assumed mass of Nemesis while Column 2 shows the corresponding minimum eccentricity of Nemesis needed to fill the loss cone of these comets as found by the computer simulations.

Table I

M_{min} / $M_\odot$	e_{min}	P_e	Fraction Lost
0.015	0.92	0.15	0.12
0.02	0.91	0.17	0.13
0.05	0.88	0.21	0.16
0.10	0.85	0.60	0.40
0.20	0.66	0.60	0.40

Averaged over time, the probability of Nemesis having a given orbital eccentricity should follow the distribution dictated by statistical equilibrium. In this case, the probability of Nemesis having an orbital eccentricity of e or larger is given by

$$P(e) = (1-e^2) \quad . \qquad (1)$$

This probability is given in Column 3 of the table. The last column of the table gives the fraction of the comets in the inner cloud that have been lost due to the perturbations of Nemesis sending them into Jupiter crossing orbits.

We may conclude from this work that the minimum mass of Nemesis needed to produce comet showers is about 0.01 $M_\odot$ or 10 Jupiter masses. If Nemesis is less massive than the Kumar (1963) limit of 0.07 $M_\odot$, it cannot be powered by nuclear burning. However, a black dwarf is observable in the infrared. It would presumably be warmer than Jupiter which has a surface temperature of 120 with most of its radiated power being due to internal sources rather than reradiated solar energy. A black dwarf with a mass of (0.01-0.07)$M_\odot$ can be expected to be about the size of Jupiter and have a surface temperature of perhaps 150-200 K. It would be one of the 2.5 × 10^5 sources in the IRAS catalog. It will be difficult to pick it out from the other sources, but its expected range of radiation temperature and expected flux will greatly reduce the number of possible candidates. It will ultimately be identified from the other candidates by its parallax.

Nemesis could also be a nuclear-burning star with a mass greater than 0.07 $M_\odot$. In this case its surface temperature would be at least 2700 K as a result of the Hayashi limit. Such an object would easily be visible with a small telescope; e.g., if its mass is 0.1 $M_\odot$, it would be about magnitude 12. If Nemesis exists, it should be found fairly soon.

D. Stability of the Orbit of Nemesis

Because Nemesis has a very large semimajor axis, we may question its long-term orbital stability. I have simulated a number of encounters between passing stars and Nemesis (Hills 1984). I find that passing stars change the orbital period of Nemesis by an average of 4% per orbital revolution. The encounters produce a slight bias towards increasing semimajor axis and orbital period of Nemesis, but basically the changes can be treated as a random walk in orbital period. In the 10 orbital revolutions spanned by the 250-million-year paleontological record of Raup and Sepkowski (1984), the accumulated change in the orbital period will be about $4\%(10^{2}) \approx 13\%$. It is not yet clear whether the degree of periodicity noted in the fossil record is consistent with such a random walk in the orbital period.

My computer simulations also show that passing stars change the orbital eccentricity of Nemesis. This can cause large percentage variations in the closest approach of Nemesis to the sun if the orbit is highly eccentric as it must be if mass of Nemesis is near its minimum possible value of 0.01 $M_\odot$. The fractional variation in the perihelion distance over 250 Myrs will be on the order of 15% for a small-mass Nemesis. Changes in the perihelion distance will cause variations in the intensity of the comet showers since it affects the minimum semimajor axes of the comets which participate in a comet shower. Thus one can expect large variations in the intensity of the extinctions depending on the eccentricity of the orbit of Nemesis. There may be large time intervals during which no extinctions occur because the orbit of Nemesis is not eccentric enough during these intervals to penetrate the inner comet cloud.

A passing star may at some point make the orbit of Nemesis so eccentric that it penetrates the planetary system. The probability that it would have entered inside the orbit of Pluto during the past 4.6 billion since the formation of the solar system is about 15%. It has been suggested that Nemesis at one time had a much smaller orbit and that stellar perturbations have caused it to walk out to its present orbit (Hut 1984). My work (Hills 1984) shows that if the semimajor axis of Nemesis were 2 × 10^4 A.U., so it were located at the inner edge of the Oort cloud, it would have a much better chance of entering the planetary system. If it had this semimajor axis for 4.6 billion years, it would have had an 80% chance of passing within the orbit of Saturn. Such a close passage would have greatly increased the orbital eccentricities of the outer planets, and it is likely to have hurled several planets into hyperbolic orbits. Because this catastrophe did not occur, we are confident that Nemesis did not spend much time near the inner edge of the Oort cloud. If Nemesis exists, it has spent most of its time near its present distance rather than in a much closer orbit.

If Nemesis had to contend only with passing stars, it would have a good chance of surviving 4.6 × 10^9 years at its present distance from the sun. However, the tidal field of the Galaxy reduces the probability of its survival (Hut 1984, Torbett and Smoluchowski 1984). It requires that Nemesis be in an orbit inclined less than 30 degees from the Galactic plane. Passing molecular clouds may also have endangered the orbit of Nemesis (Clube and Napier 1984),although this is a controversial mechanism due to great uncertainties in the masses and numbers of giant molecular clouds.

III. Final Comments

The Nemesis hypothesis remains tenable, although the recent work discussed in this review indicate some difficulties. The problems are not severe enough to eliminate the hypothesis, so its final test will have to be left to the observers. If Nemesis exists, it must be in the Infrared Astronomical Satellite Catalog, and it will eventually be identified.

Even if Nemesis does not exist, the work on Nemesis has been useful in emphasizing the fact that comet and asteroid impacts occur and they have caused enormous stress in the earth's biosphere resulting in the extinction of a significant fraction of the species on the earth. Even without Nemesis these mass catastrophes will continue to occur in the future. While these astronomical catastrophes are infrequent, they have shown themselves to be the greatest danger to life on earth.

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Jack G. Hills
Mail Stop B288
Los Alamos National Laboratory
Los Alamos, NM 87545