ASTRONOMICAL MECHANISMS AND GEOLOGIC EVIDENCE FOR MULTIPLE IMPACTS ON EARTH P. Hut[1], E. M. Shoemaker[2], W. Alvarez[3], A. Montanari[3]; [1]Inst. for Advanced Study, Princeton NJ 08540; [2]U.S. Geological Survey, Flagstaff AZ 86001; [3]Dept. Geology & Geophysics, Univ. Calif., Berkeley CA 94720

There is increasing interest in multiple impacts on the Earth, because of new information on two recent impact crises. The Eocene-Oligocene boundary interval is marked by at least 2 iridium anomalies and 3 horizons of impact spherules, indicating multiple impacts on a time scale of < 1 Myr [1, 2]. The Cretaceous-Tertiary boundary was apparently the time of at least two substantial impacts (Popigai [3], Manson [4, 5]) and perhaps at least one more (Yucatan [6]), but only a single large iridium anomaly [7], which suggests multiple simultaneous impacts. The following is a list of possible mechanisms for producing multiple impacts on the Earth:

- A. Many bodies on unrelated orbits (perturbation of the Oort Cloud)
- B. Many objects on related orbits
  - 1. Stably bound pairs of mutually orbiting objects
  - 2. Unbound, gradually dispersing sets of objects
    - a. Dispersing because of collision anywhere in Solar System
    - b. Dispersing because of disruption by Sun
      - i. Disruption through Solar tidal forces
      - ii. Disruption through Solar heating
    - c. Dispersing because of disruption by Earth
      - i. Tidal disruption by Earth during close passage
      - ii. Tidal disruption by Earth immediately before impact
- C. Secondary impacts by target fragments after primary impact

(A) Passing stars disturbing the Oort Cloud will trigger occasional comet showers, which may produce several impacts on Earth during a theoretically expected duration of order 10^6 years. This mechanism is not applicable to asteroids, since the asteroid belt is very much closer to the Sun, and will not be perturbed in this way. The Eocene-Oligocene stratigraphic evidence supporting impacts over a time scale of order 10^6 years, thus may indicate impacts by distinct comets, most likely perturbed into the loss cone by a passing star.

(B) If the impacts are clustered in time over much less than 10^6 years, they probably originate from objects on very closely related orbits, either (1) objects forming a stable, self-gravitating, bound system, or (2) an unstable, dispersing set of fragments, which have not yet dispersed to distances much greater than the cross section of the Earth.

(B.1) Objects forming a bound system must orbit each other at a relatively close distance to avoid break-up by the tidal force of the Sun. For example, a double asteroid at 1 A.U. from the Sun cannot have a separation much larger than ~ 100 times the radius of the larger of the two bodies. With so little space, it is unlikely that more than two large fragments are stably bound. A double asteroid or double comet would give rise to impact structures consisting of two craters side by side, separated by a few crater diameters at most, and such double craters have been recognized on Earth (Clearwater Lakes; Kara-Ust Kara). The first asteroid for which high-resolution radar images was obtained can be interpreted as a contact binary with each object about half a mile in diameter [8].

(B.2) Only an unstable, dispersing set of fragments can lead to more than two large impacts and/or to widely separated impacts on Earth. Such a set of dispersing objects could originate from breakup of either an asteroid or a comet, with the latter possibility more likely because of the greater strength of asteroids. (B.2.a) Breakup of an asteroid or comet due to collision with another asteroid or comet shortly before encounter with Earth has extremely low probability.

(B.2.b) A more frequent phenomenon is the breakup of a comet on its first passage near the Sun or, if it is captured in a shorter orbit, during subsequent perihelion passages. This breakup may occur through tidal disruption or by disintegration during volatile loss. Specifically, a comet with a radius of ~ 10 km will have an escape velocity of ~ 10 m/sec. Breakup at ~ 10^8 km from the Earth, with a velocity of ~ 10^2 km/sec relative to the Earth, would lead to separation of the fragments of ~ 10^4 km, comparable to Earth diameter, by the time they reach the

Earth. What can we say about the geographical distribution of impact sites of dispersing cometary fragments? When the fragments are separated by 10,000 km, travelling at a speed of about 40 km/sec, they will impact within a time interval of less than 5 minutes. During this time the Earth will have rotated by only about one degree. Therefore, we can treat all fragments as having arrived nearly simultaneously, and the craters have to be found within one hemisphere. Even the presence of one crater outside a hemisphere defined by the others invalidates the hypothesis of the breakup of a single parent body. Although the breakup may occur at a substantial distance from the Sun, even exceeding 1 AU, it is more likely to occur closer to the Sun, where heating effects are stronger. If a comet arrives at Earth after a very close encounter with the Sun, its orbit must be close to the plane of the ecliptic. An arrival from a direction either significantly to the north or to the south of the ecliptic would imply a perihelion passage at a distance of not much less than 1 A.U. However, due to the tilt of the Earth's axis, the hemispheric boundary can be tilted to include a region around either the North or South Pole, the only restriction being that that region lie withing the Arctic circle (or possibly slightly outside, if we take into account the small deviation from a purely ecliptic orbit of the incoming cometary fragments). Interestingly, the Popigai crater, while lying on a nearly opposite meridian to the Yucatan crater, did indeed lie above the Arctic circle at the time of the K-T boundary. Thus, a solar-heating disruption of a single-parent cometary body can explain the simultaneous formation of all three candidate craters associated with the K-T impact. In addition, the location of the Popigai crater near the contemporary Arctic circle could suggest that the impact took place during Northern hemisphere summer.

(B.2.c) The final possibility is breakup of a comet by tidal disruption due to the Earth. Again there are two scenarios for producing multiple impacts by this mechanism.

(B.2.c.i) If tidal breakup of a comet occurs during close passage by the Earth, cometary debris on closely related orbits will spread out into a stream of fragments. Thus, impacts may occur during annual passages of the Earth through the original point of encounter. In this scenario, the parent body will have to be of substantial size in order to produce several major impacts, since a significant fraction of the fragments will avoid impact. The duration of this type of multiple impact is limited by the dispersal time of the fragmented stream and the precession of the orbits of the fragments.

(B.2.c.ii) Breakup due to tidal effects during final approach to the Earth immediately before impact does not allow the fragments to separate sufficiently for their impacts to be distinguished either as separate craters or as separate ejecta layers. A simple estimate shows this as follows: Take an impactor with a diameter of 10 km starting to break up at 10,000 km from the Earth. In this case the tidal force across the body of the impactor will be 10^{-3} of the acceleration of the impactor toward the Earth because the impactor will come in with speed significantly above the escape velocity of the Earth, the separation of the fragments at the time of impact will be $<10^{-3}$ times the distance between the projectile and the Earth at the time of breakup. This distance, <10 km, is much smaller than the size of the crater.

Detailed study of the cratering and impact-stratigraphy record on Earth should eventually be able to establish the relative importance of the various mechanisms for multiple impacts in the history of the Earth.

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