IMPACT-INDUCED CLIMATE CHANGE DUE TO AN ORBITING DEBRIS RING

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Abstract

The effect of time-dependent incoming solar radiation (insolation) losses due to the shadow of an opaque orbiting ring around the Earth is addressed using a modified version of the atmospheric general circulation model GENESIS. Twelve simulations were run using three different sets of orbital parameters; three without rings, and nine with two different ring models. One set of simulations was performed using two different initializations as a stability and convergence check. The three sets of orbital parameters were chosen to simulate glaciation-favoring and glaciation-inhibiting conditions in the northern hemisphere, as well as current conditions. The objective was to address the question of whether a impact-generated ring could amplify or diminish certain Milankovich periods in a way that might be evident in the geologic record.

Introduction

Many ideas have been proposed for the K/T boundary extinction, including production of massive amounts of nitrogen oxides by shock-induced chemical reactions in the atmosphere, shock devolatilization of carbonate and anhydrite target rocks producing carbon dioxide and sulfur compounds, and production of a long-lived opaque aerosol layer from impact ejecta with smoke from global firestorms. Some combination of these effects would result in a large transient change in atmospheric chemistry, insolation, albedo, and long-wave radiative properties. Alvarez et al. [1] suggested that the diameter of the impactor was about 10 km based on the global quantity of iridium in the K/T boundary. The best estimate of the projectile size has not changed significantly in the years since Chicxulub has been discovered and characterized. The K/T boundary undoubtedly represents the largest impact event of the last hundred million years. However, the significance of this event has more to do with its relative recency and the particular fauna that disappeared that with its uniqueness over geologic time.

Shoemaker [2] estimated that impacts of K/T size (releasing on the order of 10^8 Mt of kinetic energy) take place on Earth with a mean recurrence interval of about 10^8 years. That rate implies that there has been a score of K/T class impacts since the beginning of the Proterozoic (about 2.5 billion years ago). Moreover, Shoemaker's power-law distribution of impact events means that since the termination of the Mesozoic Period by the K/T event, there have been ten impacts of about 10^7 Mt, a hundred events of 10^6 Mt (roughly the size of all Shoemaker-Levy 9 fragments

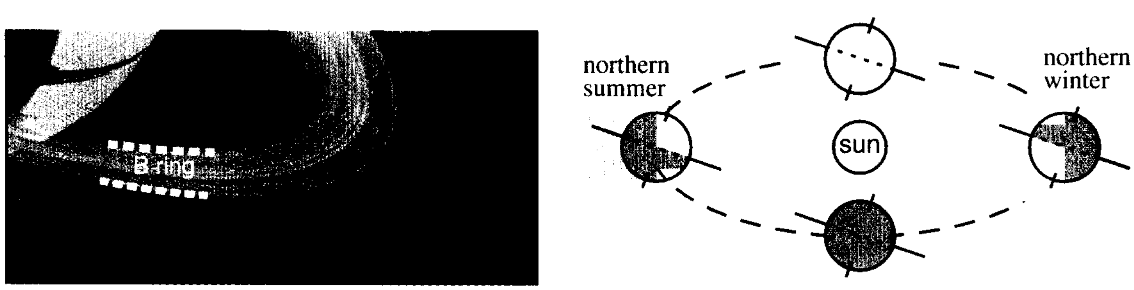

Figure 1. Voyager spacecraft image of Saturn showing the opaque B-ring and its shadow on the planet's cloud tops (left), seasonal effect of equatorial ring on insolation (right).

combined), and a thousand impacts of 10^5 Mt (about the size of the impact that asteroid 1997 XF_{11} would have made, if it had been on an Earth-intersecting path).

If climate is indeed sensitive to such events, then it is virtually certain that many of these impacts left signatures in the geologic record besides holes in the ground. The work presented here suggests that the sedimentary record might contain evidence for impacts beyond ejecta layers, and that both transient and long-term impact-generated climate effects might be seen in sedimentary rocks due to the formation of a transient debris ring in Earth orbit. Modeling of climate change by various mechanisms can provide insight to help interpret the geologic evidence.

The Geologic Record

The most obvious sedimentary record of an impact is the clay layer left by the ejecta from the K/T event. This layer was first associated with an impact because of the high concentration of platinum-group elements discovered in the clay from the K/T boundary at Gubbio, Italy. Subsequently, other evidence for impact was found in the layer, including shocked mineral grains and spherules. These observations were direct evidence for an impact, because the materials were derived from the impacting body or from the impact event itself.

One can look at the larger stratigraphic sequence and also note that there was a climatic shift at the K/T boundary. The Cretaceous and Tertiary sedimentary cycles are dominated by the approximately 20 thousand year (ky) period associated with precession. Below the boundary these are bundled into 100 ky eccentricity cycles, but that is no longer true above the boundary. This observation implies that the impact event not only caused a the large transient climate change responsible for the extinction, but that it somehow changed in the planet's sensitivity to orbital forcing for hundreds of thousands of years afterward.

Another abrupt change in sensitivity to orbital forcing took place 700,000 years ago, at virtually the same time as the Australasian tektite-forming event for which an impact structure has not yet been discovered. In this mid-Pleistocene case, obliquity-dominated (40 ky) cycles were replaced by eccentricity-dominated (100 ky) cycles which continue to persist (the "mid-Pleistocene transition").

Possible Mechanisms

Most of the proposed mechanisms for climate change caused by impacts are related to atmospheric chemistry and aerosols, and such impact-induced climate changes are usually thought to be transient, with an eventual return to pre-impact conditions. However, the changes in Milankovich sensitivity suggest that there are longer-term effects that need to be understood. Few hypotheses have been proposed to explain the shifts in orbital forcing at the end of the Mesozoic and in the mid-Pleistocene. The mechanism to be explored in this paper is the generation by a large impact of a ring that encircles the equatorial region of the Earth. The global extent of iridium, spherules, and shocked quartz at the K/T boundary clearly demonstrate that material is ejected at orbital velocities. A purely ballistic ejection that does not involve atmospheric interactions would not allow such particles to remain in orbit, and they would reenter the atmosphere and impact within one orbital period. However, atmospheric interactions are increasingly being recognized as an important component of terrestrial impact physics, and this could possibly provide the conditions that would lead to orbital trapping of debris through hydrodynamic forces within an expanding plume that alters the trajectories of some particles in such a way that they do not re-enter the atmosphere.

On dynamical grounds, one can argue that such an orbiting cloud of debris would collapse to a single plane within the Earth's Roche limit, by the same orbital mechanics that led to Saturn's ring system. The stable plane for any such planetary ring is the Laplacian plane, defined by the total angular momentum of the planetary system. Saturn is a rapidly rotating, low-density gas giant, so its system's distribution is dominated by its oblate figure: the planet's diameter is 10% greater at the equator that along its pole of rotation. A ring around the Earth would also be equatorial to first approximation, but the Moon would cause the ring plane to wobble with a period equal to that of lunar nodal regression (currently about 18.6 years)

Planetary Rings and Insolation

An equatorial ring would cast a shadow primarily in the tropics, as is the case for Saturn (Figure 1). The location, surface area, and darkness of the ring shadow would have a strong seasonal dependence, resulting in a net reduction in insolation in the winter hemisphere. The maximum insolation loss would be during the solstices, when the ring shadow is most extensive. At the equinoxes, the ring would be parallel to the subsolar direction and the shadow would be negligible.

At any latitude (ϕ), the average daily insolation at the top of the atmosphere can be written in terms of solar declination angle (δ) and distance from the sun (d):

$$\bar{Q} = \frac{S_0}{\pi}\left(\frac{\bar{d}}{d}\right)^2 [\mathrm{acos}(-\tan\phi\sin\delta)\sin\phi\sin\delta + \cos\phi\cos\delta\sin\{\mathrm{acos}(-\tan\phi\sin\delta)\}]$$

where S_0 is the solar constant and $\bar{d}$ is the mean solar distance. The simplest possible ring model assumes an opaque equatorial ring between r_{min} and r_{max}, its inner and outer distance from the Earth's center, respectively. As a first approximation for small δ, the ring shadow covers a latitude band from about and $-(r_{max} - 1)\cos\delta$. Because this is the easiest model to implement quickly, it was used it to modify the normal insolation forcing, in an atmospheric general circulation model to explore the effects of an equatorial ring. Figure 2 shows the effect of an equatorial ring (scaled to the size of Saturn's B ring) on the latitude-dependent insolation for Earth on five different days of the year.

It is noteworthy that the daily average insolation equation depends on both solar declination angle (δ) and distance from the sun (d), which have seasonal values that depend parametrically on eccentricity, precession, and obliquity. The effect of rings, however, depends only on solar declination, which in turn varies only with obliquity. Whereas the average daily insolation at a given latitude is modulated by all three orbital parameters, the ring shadow only affects the modulation due to obliquity. The existence of an equatorial ring would primarily affect obliquity forcing on global climate. It is much more obvious that a ring would lead to strong obliquity forcing of local climate in the tropics, because the obliquity determines whether or not certain locations will be in

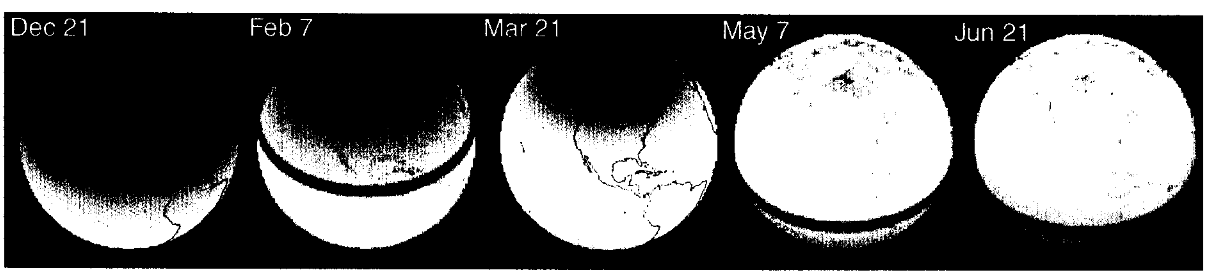

Figure 2. Daily average insolation as a function of latitude, mapped onto the Earth. Grayscale is linearly proportional to average insolation for each day. (Dark=low, Light=high).

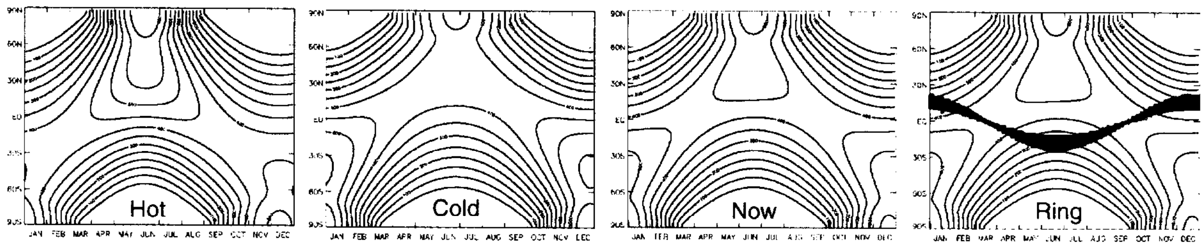

Figure 3. Contour plots of daily average insolation for various orbital parameters and for a ringed Earth. Contour interval is 50 W/m^2. Dark band is ring shadow with zero insolation.

the ring shadow, and for how long. One would therefore expect a ringed-Earth to leave a stronger obliquity signal in the geologic record than a non-ringed Earth. Moreover, the obliquity signal should manifest itself in the tropics in addition to high latitudes, even though the depositional processes are different.

To test this hypothesis, it is necessary to calculate the insolation differences for the Earth under various conditions that depend on orbital parameters and rings. Figure 3 is a set of contour plots for Earth under two extreme sets of orbital parameters ("Hot" and "Cold"), as well as under current conditions with and without a ring ("Ring" and "Now", respectively). "Now" refers to present conditions, with eccentricity e=0.017, obliquity Φ=23.5^o , and perihelion on January 5. "Hot" conditions are for the hottest northern hemisphere summer, with e=0.06, Φ=25^o , and perihelion on June 21. "Cold" conditions are for the coolest northern hemisphere summer, with e=0.06, Φ=22.5^o , and with perihelion on January 21. Global average annual insolations for the various configurations were summed and are tabulated in Table 2. The global variation in insolation is in a direction that would tend to slightly inhibit the northern hemisphere effects at the extremes due to variation in precession and eccentricity (obliquity was the same for the "Hot" and "Cold" orbital parameters). When obliquity is held constant and the other orbital parameters are varied, the insolation depends on the ring geometry. The scaled B ring does not extend to the top of the atmosphere, so more sunlight can shine underneath it in the equatorial region, and total insolation goes up with high obliquity whereas the unit ring has the opposite dependence (Table 1). Insolations should be recalculated with a more realistic ring model to improve the estimates of these small variations.

Table 1: Global average annual insolation dependence for various orbital conditions (W/m$^{2)}$

Configuration	Cold	Now	Hot	Obliq.=22.0°	Obliq.=23.5°	Obliq.=25.0°
No ring	342.2	341.8	342.4	341.8	341.8	341.8
Scaled B-ring	325.6	324.2	324.5	323.9	324.5	325.1
Unit ring	296.8	295.0	294.0	296.3	295.0	293.4

Thus far the discussion has been limited to a simplistic equatorial ring because it is relatively easy to implement using an atmospheric general circulation model to see how such a ring might influence climate. A terrestrial ring in the lunar orbital plane would vary the insolation in a much more complicated way that would not only have a seasonal component but a lunar nodal regression component with a period of about 20 years (but changing with geological time due to the recession of the moon by tidal dissipation). The insolation variation can be solved numerically, and should be the subject of future work.

Computational Climate Model Results

For the present climate simulations, the GENESIS (Global ENvironmental and Ecological Simulation of Interactive Systems) global climate model of Pollard and Thompson [3] was used. This code was developed at NCAR and is a set of coupled global models that includes atmospheric general circulation, various ocean transport options, several vegetation models, soil, snow, land ice, and sea ice. There is a surface/atmosphere coupling scheme that computes fluxes through vegetation canopies. The computational algorithm is a spectral-transform dynamics method, with semi-Lagrangian vertical transport.

The current simulations are based on intermediate-resolution parameters, with T31 spectral truncation limits for both atmosphere and surface (where T refers to a triangular shape of the Legendre function indices when values less than the truncation limits are plotted against one another, and 31 is the highest wavenumber used). This truncation limit corresponds to grid boxes that are about 3.8^{o} per side. Eighteen atmospheric levels were modeled. Each of twelve simulations was run on 8 processors of two Silicon Graphics Origin 2000-series computers at Sandia National Laboratories, with 64 IP27 processors having clock speeds of 195 MHz and arranged in hypercube topologies with total shared memories of 16 Gbytes. The T31/T31 simulations ran at a rate of about two years of model time per CPU day in this configuration.

A matrix of twelve simulations was chosen to address the question of whether a ring would change Earth's climate sensitivity to orbital forcing parameters, and if so, how much. The first set of three simulations was designed to establish baseline conditions, using the orbital parameters for current, hot-northern-summer, and cold-northern-summer conditions described earlier ("Now, "Hot", and "Cold", respectively). The extremes were chosen because summer insolation variation at high northern latitudes has been identified as the main driver of Milankovich forcing, since it determines the amount of ice that can melt in between the winters. For the second set of simulations, a modified version of GENESIS was used to model the shadow of an opaque ring scaled to Saturn's B-ring, which extends from 0.53 to 0.93 planetary radii. Each of the three orbital configurations was run twice, started two different ways to provide a check on stability and convergence. The first set was started using a restart file generated for present-day, ringless, Earth conditions. The second set was "cold-started", with the atmosphere initialized to a pre-determined zonally symmetric state with geostrophic zonal wind velocity components and zero humidity. These simulations sets are given the suffix designations "R" and "C" respectively. Similar simulations were run for a ring that extends from the top of the atmosphere to 1 Earth radius above the surface (the "unit ring" simulations). The ringless Earth simulations ran for ten years and stopped at a pre-designated time. The six B-ring simulations were run for up to twenty years. In the presentation below, the ringless Earth results are presented for the tenth year, and the B-ring results are plotted for runs that lasted anywhere from nine to eleven years. All three unit ring simulations developed a numerical stability problem that generated unrealistic atmospheric temperatures after about two years, and stopped prematurely.

The analysis is preliminary and limited to temperatures in the lowest atmospheric layer. Because the key temperatures that determine ice growth and melt are those for northern continents, three locations in North America are compared and tabulated. The positions are at three different latitudes (about 35^{o}, 54^{o}, and 72^{o}N) and are on the same meridian (about 106^{o}W). These locations roughly correspond to New Mexico, Saskatchewan, and Victoria Island, so those names will be used for convenience. July temperatures are given in ^{o}C for all three locations for the nine successful simulation runs in Table 2, where the number in parentheses is the difference between the ringed and ringless planet.

Table 2: July daily average temperatures for three locations; difference between ringed and control in parentheses.

Location	Cold	Cold R	Cold C	Now	Now R	Now C	Hot	Hot R	Hot C
New Mexico	5	6 (+1)	4 (-1)	11	11 (0)	9 (-2)	18	15 (-3)	11 (-7)
Saskatchewan	6	5 (-1)	6 (0)	13	10 (-3)	6 (-7)	15	24 (+9)	22 (+7)
Victoria Island	-9	-10 (-1)	-10 (-1)	-8	3 (+5)	-5 (+3)	-5	7 (+12)	10 (+15)

These results are surprising in many ways. One would expect that a roughly 5% reduction in global average insolation would reduce the temperatures everywhere. The solar radiation deficit in the winter hemisphere would be expected to lead to a higher temperature gradient and generate stronger transport of heat from the summer hemisphere, cooling it as well. The simulations for the cold orbital configurations show essentially no ring-related temperature effect at these locations in the summer hemisphere. The simulations for current orbital conditions show that the ring cools upper middle latitudes (Saskatchewan), but at very high latitudes (Victoria Island) there is a warming of a few degrees. The hot orbital parameter simulations provide the biggest surprise: the ring is responsible for a sharp rise in temperature in Saskatchewan of 7 to 9^0 , and the temperature rise within the Arctic circle reaches 12 to 15^0. If this result represents a real effect, then a planetary ring system could be a strong amplifier of obliquity forcing of glacial-interglacial cycles. In Saskatchewan, the July temperature difference between Hot and Cold orbital conditions is 9^0 for a ringless planet, compared to 16 to 19^0 for a ringed planet. At Victoria Island, the difference is only 4^0 for a ringless Earth, but would reach 17 to 20^0 if the Earth had a B ring. The July temperatures are plotted for cold and hot conditions in Figure 4.

Other notable results are temperatures below -30^0C in the Sahara desert and in the Amazon Basin, within the ring shadow. This leads to a large increase in the meridional temperature gradient over north Africa, generating a much stronger westward tropospheric jet that extends across the Atlantic, and through the Caribbean. This jet is much more intense, and further north than the normal westward jet that creates the conditions responsible for Atlantic hurricanes, implying that such storms are more frequent and intense for a ringed Earth. Because heat is transported into the ring shadow more efficiently in the ocean that on continents, the land-sea temperature gradient is greater for the ringed Earth, leading to more intense monsoons. A detailed climatological analysis of a ringed Earth is presented by Fawcett and Boslough [4].

Cold Control | Cold B-ring | Hot Control | Hot B-ring

Figure 4. July daily average temperatures for two orbital configurations for ringless (control) and scaled B-ring simulations. Darkest blue is -30^0 C, and darkest red is 35^0 C.

Discussion

Until more simulations and analyses can be done, the explanation for ring-enhanced high latitude northern hemisphere summer temperatures can only be speculative. The implications for late Pliocene to mid Pleistocene glacial-interglacial cycles are the most intriguing. The ocean sediment $\delta^{18}O$ proxy record for ice abundance during this span of time [5] shows a strong 40-ky signal up until about 700 ky before present. At that time there was a switch to a 100-ky-dominated oscillation with much higher amplitude. The 40-ky period is almost certainly associated with obliquity forcing, which implies that the Earth's climate system went through a major transformation 700 ky ago that decreased its sensitivity to obliquity forcing. One possibility is that Earth had a ring system prior to that time, and its disappearance resulted in the observed climate transition.

This suggestion immediately leads to a whole host of questions. How did the ring form? What was it made of an how much mass would be required? How did it disappear? Recent 3D computational simulations (David Crawford, personal communication) have shown that for a oblique asteroid impact, with an entry angle of less than 15^{o} , the entire asteroidal mass--as well as significant quantities of ocean water and crustal rock--can be ejected at velocities approaching escape velocity. It is reasonable to expect that some of this material would be captured into a stable set of orbits by a combination of atmospheric interactions, hydrodynamic forces, and interparticle interactions. The surface area of a B-like ring scaled to Earth's radius is about 1.8×10^{18} cm^2. About 10^{17} g of mm-size particles (assuming a density of about 3 g/cm^3) would be required for the ring to have an optical depth of unity, which would be nearly opaque for the range of solar declination angles experienced. A 10 km-diameter asteroid, about the same as the estimated size of the K/T impactor, would be required if its entire mass went into the ring. Micron-size particles, typical for Jupiter's rings, would required the mass equivalent of a 1 km asteroid. However, such small particles are probably unrealistic because Poynting-Robertson drag (deflections from photon interactions) and plasma drag with the Earth's magnetospheric plasma would severely limit the lifetime of such a ring. The Saturnian and Uranian ring system particles are estimated to be centimeters to meters in diameter. This would require much more mass for significant opacity. Nevertheless, if the enhancement of obliquity forcing is as strong as the climate simulations suggest, a ring with modest opacity might lead to significant amplification.

It is possible that an existing ring system could be sporadically replenished by random asteroid or comet collisions. There were several significant impacts during the Pliocene and Pleistocene. One of the largest was the Eltanin event in the southeast Pacific, about 2.3 million years ago. The estimated asteroid diameter is 0.5 km, but it could have been as large as 2.0 km if the impact angle was oblique ($<15^{o}$ entry angle). Kyte et al. [6] believe that the time of the impact is unresolvable from the onset time of Northern Hemisphere glaciation (between 2.5 and 3.0 million years ago) and suggest that this could have been caused by the injection of at least 2×10^{15} g of seawater into the atmosphere, which saturated the atmosphere and generated global high-altitude clouds, ultimately leading to lower temperatures and more continental area covered by snow. The time of the Eltanin impact also seems to correlate with a shift in the marine oxygen isotope record that is consistent with several periods of much greater than usual ice cover at that time. Another potential ring-replenishing event could be the impact associated with the formation of the Lake Bosumtwi crater in Ghana about 1.1 million years ago.

Perhaps even more provocative is the possibility that such a ring did not gradually erode but disrupted catastrophically about 760,000 years ago, resulting in the Australasian tektite strewnfield--which has no known associated impact structure--and accounting for the sudden departure from strong obliquity period dependence of ice quantity evident in the oxygen isotope record. The

Muong-Nong Tektites of southeast Asia have been particularly difficult to explain because they appear to have formed from vitrification of soil over an extensive area, which seems inconsistent with a single impact. Boslough and Crawford [7] suggested that a swarm of impactors simultaneously entered the atmosphere over a large region, generating a collective atmospheric plume that collapsed and heated the atmosphere. This in turn radiatively melted the soil, which was rapidly quenched by heat conduction into the cooler substrate. The weakest part of this hypothesis has been the lack of an explanation for a source of the necessary tightly-correlated swarm of debris. This would be resolved if the impactors were from a collapsing ring, but the revised hypothesis requires an explanation for why such a collapse would be sudden.

The Goldreich-Tremaine [8] model for ring stability invokes the existence of shepherd satellites. An inner satellite moves in a faster, lower orbit, and continuously gives up some of its orbital energy to ring particles, forcing them into higher orbits. On the other side, an outer slower satellite captures energy from the ring particles thereby pushing them into a lower orbit. If both shepherds are present, then a narrowly "collimated" ring can be stable. However, such a ring has a limited lifetime, with the whole system loses energy due to various drag forces, and the inner shepherd's orbit will eventually decay until it enters Earth's atmosphere. This would be expected to cause a loss of ring focusing from the inside, leading to an instability with eventual dissipation of the ring. However, because of the shepherd entry event itself, the rest of the ring can collapse within one orbit due to the generation of an atmospheric plume [7]. When the shepherd deposits its kinetic energy into the Earth's atmosphere, a Shoemaker-Levy-like plume would be ejected hundreds of kilometers into space, directly into the path of the ring particles. The ring particles that collide with the plume would lose their kinetic energy and vaporize, increasing the plume's mass and internal energy. Because the ballistic trajectory would keep the plume aloft long enough for a significant fraction of the ring to accrete, the plume's growth would be a runaway process with mass and energy being added at a faster rate than it dissipates, catastrophically consuming the entire ring and disrupting the Earth's atmosphere.

This phenomenon is extremely speculative and has never been modeled, but there are other lines of evidence that might provide support. The Australasian strewn field spans the equator, and the Muong-Nong tektites are at a latitude that would be within the range of a ring in the lunar orbital plane. Generation of objects large enough to be shepherd moons is difficult by impact, but not out of the question. Schultz and Gault [9] demonstrated that fragments up to 10% of the impactor diameter can be placed into very eccentric orbits for oblique impact angles of less than 15^{o}. The K/T boundary, which might be associated with another ring-producing impact, does not have the sharp iridium spike right at the boundary, as one might expect for a single layer of ejecta derived from an extraterrestrial object. Instead, the iridium-rich material is found only at he top of a complex K/T sequence, suggesting that there was a re-accretion of material ejected into orbit [10]. If speculations about the existence of impact-generated planetary rings have any merit, then one would expect to eventually find more compelling evidence in the geologic record.

Conclusions

Comparison of the results of climate simulations for a ringless and ringed Earth reveal that the winter hemisphere is much colder for a ringed Earth. This would be expected because in the winter hemisphere, insolation is reduced by an equatorial ring. At northern mid-to-high latitudes, the winter temperatures are as much as 9^{o}C colder in January in North America. The amount of winter cooling shows no clear trends; it is roughly the same for all orbital conditions examined. However, the summer high-latitude insolation varies with obliquity in an unexpected way for a ringed

Earth. In Canada and Siberia, the high obliquity July temperatures are as much as 10 to 15°C warmer for a ringed planet. This increase is compensated by a decrease at lower latitudes. For the other orbital conditions, the same high-latitude locations are within a few degrees. This result is significant because high latitude summer temperatures control the formation of ice sheets.

The high northern latitude summer temperature increases for a ringed Earth are difficult to explain without further work, but if the result is true it means that the existence of rings would amplify the greenhouse/icehouse cycle with a 40,000 year period. Combining this result with the $\delta^{18}O$ proxy record for ice abundance leads to the speculation that Earth had a ring system during the late Pliocene and early Pleistocene, and that it eroded and disappeared about 700,000 years ago, approximately coincident with the formation of the Australasian tektites. This suggestion is tentative, and currently has a only a weak foundation in both impact physics and climatological modeling. No modeling of ring dynamics has been done to determine the stability and lifetime of a hypothetical terrestrial ring system, how it would form, evolve, decay, and disappear. The physics of ring-forming impacts, orbital dynamics of such rings, and climatology of a ringed Earth are all fertile areas for more computational research to be guided by this working hypothesis.

References

1. Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel (1980), "Extraterrestrial cause of the Cretaceous/Tertiary extinction", *Science* **208**: 1095-1108.
2. Shoemaker, E.M. (1983), "Asteroid and comet bombardment of the Earth", *Ann. Rev. Earth Planet. Sci.* **11**: 461-494.
3. Pollard, D., and S.L.Thompson (1992), "Users' guide to the GENESIS global climate model version 2.0", National Center for Atmospheric Research, Boulder, Colorado, 58 pp.
4. Fawcett, P.J. and M.B.E. Boslough (2001), "Climatic effects of an impact induced equatorial debris ring", *J. Geophys. Res,* submitted.
5. Raymo, M.E., W.F. Ruddiman, N.J. Shackleton, and D.W. Oppo (1990), "Evolution of Atlantic-Pacific δC^{13} gradients over the last 2.5 m.y.", *Earth. Planet. Sci. Lett.* **97**: 353-368.
6. Kyte, F.T., L. Zhou, and J.T. Wasson (1988), "New evidence on the size and possible effects of a late pliocene oceanic asteroid impact", *Science* **241**: 63-65.
7. Boslough, M.B.E. and D.A. Crawford (1997), "Shoemaker-Levy 9 and plume-forming collisions on Earth", *Annals of the New York Acad of Sciences* **822**: 236-282.
8. Goldreich, P. and S. Tremaine (1982),"The dynamics of planetary rings", *Ann. Rev. Astron Astrophys.* **20**: 249-283.
9. Schultz, P. H. and D.E. Gault (1989), "Protracted global catastrophes from oblique impacts", *Lunar and Planet. Sci. Conf.* **20**: 970-971.
10. Rocchia, R., Robin, E., Froget, L, and Gayraud, J. (1996), "Stratigraphic distribution of extraterrestrial markers at the Cretaceous-Tertiary boundary in the Gulf of Mexico area: Implications for the temporal complexity of the event", *GSA Special Paper* **307**: 279-286.

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