A Late Miocene Dust Shower Produced by a Breakup in the Main Asteroid Belt

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Comet showers and asteroid collisions are important events that can affect the bombardment history of Earth and other terrestrial planets for millions of years. Because they are generally stochastic in origin, their occurrence can be deduced only from evidence in some appropriate archive. Analysis of orbital properties indicates that the Veritas asteroid cluster was produced by the disruption of a 150 km diameter asteroid 8.3 ± 0.5 Myr ago. Here we present completely independent evidence for this event: the disruption coincides with a large transient increase in the flux of interplanetary dust accreting to Earth as recorded by ³He in marine sediments. The increase began at 8.2 ± 0.1 Myr ago, reached a maximum of ~4 times pre-event levels, and dissipated over ~1.5 Myr. For this period the terrestrial IDP accretion rate was overwhelmingly dominated by Veritas family fragments. The duration and magnitude of the dust event and the absence of an asteroid shower at this time are both quantitatively reasonable for an asteroid collision. Over the last ~10⁸ yr no other event of this magnitude can be deduced from main belt asteroid orbits. One remarkably similar event is present in the ³He record 35 Myr ago, but its origin by comet shower or asteroid collision remains uncertain.

Throughout solar system history the Earth has been bombarded by interplanetary dust particles (IDPs): asteroid and comet fragments ranging from ~1 to 1000 µm in diameter. This inner solar system dust is believed to be in quasi-steady state, with the particles created by episodic main belt collisions or cometary fragmentation replacing those removed by comminution, dynamical ejection out of the inner solar system, and planetary or solar impact. After release, IDPs spiral toward the Sun under the effects of non-gravitational forces including Poynting-Robertson and solar wind drags. At the same time, implantation of solar wind ions enriches IDPs in ³He. If these particles avoid intense frictional heating during atmospheric entry, they can reach the Earth’s surface with their ³He intact. Thus, the amount of ³He in seafloor sediments gives us a unique means to quantitatively probe the major events that have affected the IDP flux and its asteroid and/or comet source bodies over geologic time.

To this end, we have obtained ³He data on sediments spanning the last 70 Myr (refs 2, 7-9), with new data in the interval 3-38 My ago reported here. We analyzed ~140 equally spaced samples from a slowly accumulating pelagic carbonate sediment (ODP Site 757,
Indian Ocean). These data were supplemented as necessary by higher temporal resolution measurements at Site 757 and also in an expanded pelagic carbonate section (ODP Site 926, Atlantic Ocean). Details of the samples, analytical methods, data, and age models are provided in the Supplemental Material.

Our $^3$He measurements indicate the IDP flux is characterized by a somewhat bumpy continuum punctuated by sharp peaks at about 8.2 and 35 Myr ago (Figure 1). The older of these peaks, in the Late Eocene, was described from a different locality earlier. This peak is well above the average of the last 70 Myr and is coincident with the formation of the two largest terrestrial impact craters of the Cenozoic Era, Popagai crater in Siberia and Chesapeake Bay crater off the eastern US seaboard. The simultaneous increase in the dust and large body flux, and the match between the duration of the dust spike and that predicted for the ejection time-scale of long period comets, were originally taken as evidence for a comet shower perhaps produced by a close stellar encounter. Recent investigations of impact melt at Popagai crater, however, suggest an L-chondrite impactor. This conclusion raises important questions about the cause of the Late Eocene event and implies that asteroids rather than comets may produce the spikes in IDP flux. Although several other episodes of elevated flux have been hinted at, none have been confirmed by high resolution work.

To further investigate the source of the Late Miocene (8.2 Myr) peak, we studied the event at higher temporal resolution (Figure 2). At Site 757 the onset of this peak coincides with the first occurrence of the index fossil *D. quinqueramus* (a morphotype of *D. bergrenni*), which has an astronomically calibrated age of 8.2 Myr (ref 10). To test that this $^3$He peak is global, we used this tie point to select and analyze coeval sediments from Site 926, located more than 10,000 km from Site 757. Site 926 was selected because it has both an astronomically calibrated age model and very high resolution biostratigraphy.

A $^3$He flux peak beginning 8.2 Myr ago and with nearly identical relative magnitude (factor of ~4 above pre-event values) and duration (~1.5 Myr) is apparent at both sites. The only major distinction between the two records is that the flux at Site 926 is always about three times higher than at Site 757. This likely reflects the effects of sediment focusing, which is known to occur at Site 926. Given the similarity of the $^3$He peak at these two sites, and the fact that the peak is not correlated with changes in sediment composition or sedimentation rate (Supplementary Material) it seems unlikely that it is an artifact of changes in deep sea circulation or sediment focusing. Furthermore, at both sites the flux peak corresponds to peaks in $^3$He concentration, $^3$He/$^4$He ratio, and $^3$He/non-carbonate fraction (Figure S1 in the Supplemental Material). These observations all indicate an increase in the IDP flux. Thus we conclude that this Late Miocene $^3$He peak, like that in the Late Eocene, is a global signature of a significant IDP-producing astronomical event.

While the Late Miocene and Late Eocene $^3$He peaks are similar in duration and magnitude (Figure 1), there is one important difference. Unlike the Late Eocene with its two large impact craters that demand an increase in the large body flux coincident with
the IDP spike, no Late Miocene craters have yet been found. Apparently the Late Miocene event was not accompanied by an asteroid or comet shower. This suggests the need for a mechanism capable of dramatically increasing the flux of IDPs striking Earth without affecting the flux of larger bodies.

We believe the best candidate mechanism for the late Miocene dust event is the disruption of the $D \sim 150$ km asteroid Veritas $8.3 \pm 0.5$ Myr ago$^1$ (Figure 3). This event produced the Veritas asteroid family, a cluster of fragments on similar orbits at $\sim 3.17$ AU. Numerical modeling indicates Veritas was, by far, the largest asteroid disruption event to have occurred in the last $10^8$ yrs (refs 1,13). In fact, it was so large that collisions between family members still produce as much as 10% of all Solar System near-ecliptic dust$^{14-16}$. The age of the family, which corresponds precisely with the onset of the Late Miocene $^3$He spike, was determined by tracking the orbits of Veritas family members backwards in time to their formation (for details, see Figure 3).

When the parent body of Veritas disrupted, it ejected almost half of its mass in the form of fragments ranging from µm-size dust grains to multi-km asteroids$^1$. These bodies then experienced dynamical evolution according to size. The evolution of small fragments ($D = 1$-1000 µm) was dominated by planetary perturbations and non-gravitational forces, which caused them to spiral inwards toward the Sun. In contrast, larger fragments ($D > 1000$ µm) were trapped in the main belt unless they could reach a chaotic resonance capable of placing them onto a planet-crossing orbit. The nearest resonances capable of producing an asteroid shower are $\sim 0.05$ AU from the Veritas family (e.g., the 9:4, 11:5, or 2:1 mean motion resonances with Jupiter). This distance would either require huge ejection velocities from Veritas (that are not observed) or extremely long drift times via Yarkovsky thermal forces (which would fail to produce a spike of impactors). Moreover, these resonances are very unlikely to produce Earth impactors$^{17,18}$. Thus, the Veritas family-forming event almost certainly did not produce an asteroid shower on Earth, so the absence of craters of this age is unsurprising.

To investigate under what conditions the Veritas collision might produce a dust spike similar to that defined by the $^3$He record, we developed a statistical Monte-Carlo model to track the collisional and dynamical evolution of particles formed by the disruption of Veritas. The results of our code were calibrated by modeling the evolution of dust in several latitudinal bands observed by the Infrared Astronomical Satellite (IRAS)$^{16}$. To compare our Monte Carlo results with the $^3$He data, we calculated the flux of $D = 10$ µm particles reaching 1 AU. Particles of about this size can escape intense atmospheric entry heating and He loss, and currently dominate the flux of extraterrestrial $^3$He to Earth$^5$. Since we do not yet have a model of $^3$He implantation in IDPs, nor one for heating and helium retention during atmospheric entry of IDPs produced during the dust spike, here we simply compare our model 1 AU flux with the shape and duration of the $^3$He peak.

Small particles from the Veritas family were assumed to reach Earth through Poynting-Robertson and solar wind drag. The production rate of the first-generation particles that were started at $3.17$ AU was defined as $P(D, t)$, where $D$ is diameter and $t$ is the elapsed time since the family formed. Motivated by results from main belt collisional evolution
models\textsuperscript{13}, we assumed $P(D,t)$ has a segmented cumulative power-law size frequency distribution with index $\alpha_i$ in the interval $(D_{\text{min}}, D_{\text{break}})$ and $\alpha_c$ in the interval $(D_{\text{break}}, D_{\text{max}})$. We assumed that collisional and dynamical evolution causes $P(D,t)$ to vary such that $D_{\text{break}}$, the diameter at which the power-law slope changes, increases with time according to:

$$\log_{10}\left(\frac{D_{\text{break}}}{D_{\text{min}}}\right) = \log_{10}\left(\frac{D_{\text{max}}}{D_{\text{min}}}\right)\left[1 - \exp\left(-t/\tau_{\text{decay}}\right)\right]$$

with $D_{\text{min}} = 10 \mu m$, $D_{\text{max}} = 1 cm$, and $\tau_{\text{decay}}$ a characteristic decay constant that will be further described below. The rate of IDP disruptions is defined by the collisional lifetime, $\tau_{\text{col}}(D,R)$ that was set to be a function of diameter $D$ and heliocentric distance $R$. For our production runs, we used published $\tau_{\text{col}}(D,R)$ estimates\textsuperscript{19}. When a particle disrupts, we replace it with a swarm of fragments that follow a power-law size distribution. We assumed that the mass of the largest fragment was half that of the parent particle. The power law index of the fragment size distribution was determined by mass conservation\textsuperscript{20}. A single simulation thus propagates the histories of $10^8$-$10^9$ particles.

The collisional lifetime of 10 $\mu m$ IDPs at 1 AU is 20 - 200 ky depending on model assumptions. The shortest lifetimes are much shorter than the $\sim 40$ ky it takes to migrate from Veritas all the way to 1 AU. A common feature of the collisional lifetime models is a very short $\tau_{\text{col}}$ for $D = 1$-$5$ mm particles ($\sim 100$ ky or less) whose break-up products significantly contribute to the IDP population after Veritas parent body disruption. This means that the $^3$He signal must have been produced by fragments from a collisional cascade that was constantly fed new material by disruption events occurring both near the Veritas source region and en route to Earth.

For Eq. (1), we ran a number of trial cases to determine a reasonable range of input parameters. Our full production runs then used $\alpha_1 = -2$, -2.25, -2.5 and $\alpha_2$ values between -3 and -4. The former values are shallower than the canonical value of -2.5 (ref 21) because Poynting-Robertson drag quickly removes small particles from the main belt, while the latter values are steeper because we need to link our size distribution to the observed members of the Veritas family while also conserving mass. We also tested values of $\tau_{\text{decay}} = 0.5, 0.75,$ and $1$ Myr, where the timescales were drawn from collision code experiments\textsuperscript{13}.

We found that the initial breakup of the Veritas family likely produced an IDP population that dominated the main belt population by at least an order of magnitude for $\sim 1$ Myr. This would explain both the shape and the decay time of the $^3$He peak. Our best match (Figure 2) comes from $\alpha_1 = -2.5, \alpha_2 = -3.3$ and $\tau_{\text{decay}} = 1$ Myr. All the major features of the $^3$He data are reproduced. Thus, the Late Miocene event allows us to glean insights into the size distribution of particles produced by the Veritas breakup at 3.17 AU and how it changes with time. For example, the breakup event produced a steep distribution of small particles which then evolved via collisional and dynamical processes to a shallower slope over Myr timescales. This result, however, is not entirely unique. The most suitable parameters $\alpha_2$ and $\tau_{\text{decay}}$ are correlated, with a longer $\tau_{\text{decay}}$ timescale.
producing the same solution as a steeper $\alpha_2$. Still, our results allow us to rule out (i) steep $\alpha_2$ values and $\tau_{\text{decay}} < 0.5$ Myr values that produce shorter $^3$He peaks than those observed and (ii) shallow $\alpha_2$ and $\tau_{\text{decay}} > 1.5$ Myr values that create longer $^3$He peaks than those observed.

Today, collisions in the Veritas family not only produce one of the prominent dust bands observed by IRAS, but they also contribute at least 5 million kg per year to the IDP flux striking Earth (~10% of the total impact flux). Our model results suggest the IDP flux from the Veritas family will continue to decay for an additional several tens of Myr until it reaches a collisional steady state and takes on the same approximate shape of the overall main belt size distribution for $D < 5$ km bodies.

Interestingly, the age of the Late Miocene event roughly coincides with cosmic ray exposure ages of 7-8 Myr obtained on about half of all H-chondrite meteorites. The connection between the events, however, is unclear. As described previously, the nearest powerful resonances are not only ~0.05 AU from Veritas family members but also they are highly inefficient at producing Earth impactors. Moreover, mineralogical and spectroscopic differences between Veritas family members and the H-chondrites indicate the former almost certainly did not originate on the latter. We also find it highly unlikely that the projectile that produced the Veritas parent body was the source of the H-chondrites, partly for the reasons above but also because the H-chondrites do not show evidence for significant shocks at 7-8 Myr ago. If the two events are indeed linked, we postulate that Veritas family members disrupted a well-positioned fragment from the H-chondrite parent body shortly after the family-forming event took place. More work on this issue is clearly needed.

Previous work has suggested a possible link between the interplanetary dust accretion rate and Earth’s climate. Correlations between extraterrestrial $^3$He in sediments and global climate in the Quaternary may support this suggestion but also may be an artifact of climate-induced changes in sedimentation. Modest global cooling and strengthening of the Asian Monsoon occurred in the Late Miocene. At Site 926 there is a sharp transition from kaolinite-rich to illite-rich sediment occurring within the $^3$He peak but 200 kyr after its onset (Figure 2). This transition may document a change from warm humid to cold dry continental weathering. Although the relative timing of these events is suggestive, we caution that a compelling link between the events cannot be established until a plausible mechanism is found by which IDPs can change climate.

Given the success of our model in matching the Veritas breakup to the Late Miocene $^3$He event and the similarity in the $^3$He patterns at ~35 and ~8.2 Myr ago, it is plausible that an asteroid collision also produced the Late Eocene peak (Figure 1). However, we find no evidence for disruption of an asteroid larger than ~100 km diameter in the main belt other than Veritas over the last ~100 Myr (ref 1). Moreover, because the Late Eocene event must also produce a short-lived but prominent asteroid shower to account for the two large craters, candidate families must inject numerous bodies into a resonant “escape hatch” that can quickly move this material onto Earth-crossing orbits. It is unclear whether any recently-formed families are consistent with this criterion. Finally,
not just any escape hatch will do; we need one that will produce several large terrestrial impactors from a limited quantity of projectiles. More work will be needed to determine whether any main belt family can match these constraints.
Figure Captions

Figure 1.

Composite record of $^3$He flux as a proxy of the IDP accretion rate for the period 3 to 70 Myr ago. New data are indicated by individual data points. Solid lines are 3-point running means through the data points, taken to minimize the effects of occasional sampling of large individual IDPs. Red line indicates the Late Miocene event, blue line the remainder of the new data set. Green lines are published results from the Late Eocene and Cretaceous to mid-Tertiary.

Figure 2.

Extraterrestrial $^3$He flux through the Late Miocene event at A) Site 757 and B) Site 926. Note the similarity of the peak recorded at the two sites, supporting a global increase in IDP flux at 8.2 Myr ago. The modeled 10µm IDP flux following the Veritas collision is shown by the black curve. The model dust spike was positioned at 8.25 Myr ago and scaled to align with the $^3$He peak. The fast rise time and ~1.5 Myr decay time observed in the $^3$He record at both sites are well matched by the model. The inferred time of Veritas breakup is indicated (see Figure 3 for details).

Figure 3.

Convergence of nodal longitudes suggests that the Veritas family formed by a catastrophic collision at 8.3 ± 0.5 Myr ago, gray band. Immediately after the disruption, the fragments all circled the Sun, as a group, in nearly identical orbits. Over time planetary perturbations forced their orbital orientations (specified by the longitude of the ascending node and argument of perihelion) to drift away from each other, eventually spreading out uniformly. By numerically integrating the present orbits of large asteroid members of the Veritas family back in time, we discovered a clustering of nodal longitudes. The figure shows orbital histories of nodal longitudes relative to that of large member asteroid (1086) Nata ($\Delta\Omega$). The mean $\Delta\Omega$ is ~40° at t ~ 8.3 Myr, much smaller than at other times, suggesting a strong statistical significance of the nodal alignment. We do not show differential evolutions of perihelion arguments because these evolutions are too fast to be useful.
REFERENCES


Figure 1
Figure 2

A) Site 757

B) Site 926

Extraterrestrial \(^3\)He flux (10\(^{-15}\) mol cm\(^{-2}\) kyr\(^{-1}\))

Veritas Breakup

illite kaolinite

Model 10 \(\mu\)m Veritas IDP Flux (Relative)
Figure 3