A late Miocene dust shower from the break-up of an asteroid in the main belt

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Throughout solar system history Earth has been bombarded by interplanetary dust particles (IDPs): asteroid and comet fragments of ~1 to 1000 μm diameter. The IDP flux 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, and planetary or solar impact. Because IDPs are rich in ^{3}He, seafloor sediment ^{3}He concentrations provide a unique means to probe the major events that have affected the IDP flux and its source bodies over geologic time[1-4]. Here we report that collisional disruption of the >150 km diameter asteroid that created the Veritas family at 8.3±0.5 Myr ago[5] also produced a transient increase in the flux of interplanetary dust-derived ^{3}He. 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. Over the last ~10^8 yr no other event of this magnitude has yet been deduced from main belt asteroid orbits.

One remarkably similar event is present in the ^{3}He record 35 Myr ago, but its origin by comet shower[1] or asteroid collision[6] remains uncertain.

After release from their comet or asteroid parent bodies, IDPs spiral toward the Sun under the effects of non-gravitational forces including Poynting-Robertson (P-R) and solar wind drags[7]. P-R drag occurs when dust grains revolving around the Sun absorb solar photons and then reradiate the energy in all directions. At the same time, implantation of solar wind ions enriches IDPs in ^{3}He. If these particles avoid intense frictional heating during atmospheric entry, they can reach the Earth's surface with their ^{3}He intact[8]. We have obtained ^{3}He data on sediments spanning the last 70 Myr (refs 1, 9, 10), with new data in the interval 3-38 Myr ago reported here. We analyzed two pelagic carbonate cores: ODP Site 757 in the Indian Ocean over this entire interval, and Site 926 in the Atlantic Ocean in the Late Miocene.

^{3}He measurements indicate the IDP flux is characterized by a somewhat bumpy continuum punctuated by sharp peaks at 8.2 and 35 Myr ago (Figure 1). The older of these peaks, in the Late Eocene, has been described from a different locality[1]. 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 and Chesapeake Bay. 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 taken as evidence for a comet shower, perhaps produced by a close stellar encounter[1]. However the composition of impact melt at Popagai crater suggests an L-chondrite impactor[6], implying 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 yet been confirmed. Possible connections between the Late Miocene and Eocene events are further discussed in Supplementary Material.

To assess the distribution and temporal evolution of the Late Miocene (8.2 Myr) peak, we studied the event at higher temporal resolution (Figure 2) at Site 757 and also at Site 926. 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 records is that the flux at Site 926 is about three times higher than at Site 757. This likely reflects the effects of sediment focusing, which is known to occur at Site 926 (ref 11). Given the similarity of the ^{3}He peak at these two sites, and the fact that the peak does not correspond to dramatic changes in sediment composition or sedimentation rate (Supplementary Material) it seems unlikely that it is a sedimentation artefact. 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 Supplementary Material). These observations indicate an increase in the IDP flux[9]. Thus we conclude that this ^{3}He peak, like that in the Late Eocene, is a global signature of an 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 increasing the flux of IDPs striking Earth without affecting the flux of larger bodies. A likely candidate is the disruption of the $D > 150$ km asteroid that produced the Veritas family, a cluster of fragments on similar orbits at 3.17 AU. The Veritas event was the largest asteroid disruption in the last 10^{8} years (refs 5,12); resulting collisions still produce as much as 10% of all Solar System near-ecliptic dust[13-15]. The age of the family, 8.3 ± 0.5 Myr ago[5] was determined by tracking the orbits of Veritas family members backwards in time to their formation (for details, see

Figure S4 in the Supplementary Material), and coincides with the onset of the Late Miocene ^{3}He spike.

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[5]. 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 ~0.1 AU from the Veritas family[16] (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). For reference, Yarkovsky drift occurs when small asteroids absorb solar photons, heat up, and then reradiate the energy away in a non-isotropic manner after a short delay[7]. 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 not surprising.

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. (Model details can be found in the Supplementary Material). The results of our code were calibrated by modelling the evolution of dust in several latitudinal bands observed by the Infrared Astronomical Satellite (IRAS) (see Ref. 15 for details). To compare our model 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 ^{3}He flux to Earth[8]. 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 P-R and solar wind drags. The production rate of the first-generation particles that were started at 3.17 AU was defined using a "broken" cumulative power-law size frequency distribution (SFD) with two slopes, index α_1 at smaller sizes and α_2 at larger sizes. The SFD extends from D = 10 μm to 1 cm. We assume the SFD decays exponentially with time from collisional evolution and radiation drag forces. This causes the diameter of the knee between α_1 and α_2 to increase with time. The rate of IDP disruptions was defined as a function of diameter D and heliocentric distance R (Ref 19). When a particle disrupts, we replace it with a swarm of fragments that follow a power-law SFD. 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[20]. Thus, in our simulations, we follow several generations of particles produced by a collisional cascade; typical runs track the histories of 10^8-10^9 particles.

We find that D = 10 μm IDPs from Veritas reach 1 AU in ~ 40 ky, typically shorter than their collisional lifetime (20 - 200 ky, depending on model assumptions[19]). This means the ^{3}He signal at Earth would be extremely brief unless these particles are continuously replenished in some fashion. The Veritas breakup, however, produced a SFD of fragments. We note that D = 1-5 mm particles have short collisional lifetimes[19] (< 100 ky), such that their fragments not only replenish the D = 10 μm population but also create intermediate-size particles that also dynamically evolve and disrupt over time. This means that the ^{3}He signal was produced by fragments from a collisional cascade that was fed new material by disruption events occurring both near the Veritas source region and *en route* to Earth.

The Late Miocene event allows us to glean insights into the SFD of particles produced by the breakup and how it changes with time. We found that the initial breakup of the Veritas family likely produced a swarm of IDPs that dominated the main belt population by at least an order of magnitude for ~1 Myr. Our best fit to the shape and the decay time of the ^{3}He peak comes from using $\alpha_1 = -2.5$ and $\alpha_2 = -3.3$ (Figure 2). We found that α_2 values significantly shallower or steeper than our best fit value produce ^{3}He peaks that are longer or shorter, respectively, than those observed.

Today, collisions in the Veritas family produce one of the prominent dust bands observed by infrared telescopes, and also contribute at least 5 million kg per year to the terrestrial IDP flux[15]. Our modelling suggests the IDP flux from the Veritas family will continue to decay for 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[21].

The Late Miocene event roughly coincides with cosmic ray exposure ages of 7-8 Myr on many H-chondrite meteorites[22]. The connection between these observations, however, is unclear. As described previously, the nearest powerful resonances are not only ~0.1 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 latter almost certainly did not originate on the former[23]. We also find it highly unlikely that the projectile that produced the Veritas family 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[24]. 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.

Previous work has suggested a possible link between the IDP accretion rate and Earth's climate[25]. Correlations between extraterrestrial ^{3}He in sediments and global climate in the Quaternary may support this suggestion[9] but also may be an artefact of climate-induced changes in sedimentation[26]. Modest global cooling and strengthening of the Asian Monsoon occurred in the Late Miocene[27]. At Site 926 there is a sharp transition from kaolinite-rich to illite-rich sediment[28], 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.

Figure 1.

Composite record of ^3He flux as a proxy of the IDP accretion rate for the period 3 to 70 Myr ago, showing several intervals of elevated ^3He flux, notably at ~35 Myr ago (Late Eocene) and ~8 Myr ago (Late Miocene). Symbols are new ^3He measurements from ODP Site 757 (central Indian Ocean, 17°01.458'S, 88°10.899'E). Solid lines are 3-point running means through the data points, taken to minimize the effects of occasional sampling of large individual IDPs[10]. Grey lines highlight the Late Miocene event (also indicated by open symbols), and the previously reported Late Eocene peak from the Italian Appenines[1]. Black line and filled symbols are the remainder of the new data set. Cretaceous to mid-Tertiary data are from Mukhopadhyay et al.[10]. Details of the new samples, analytical methods, data, and age models are provided in the Supplementary Material.

Figure 2.

The extraterrestrial ^3He flux peak (gray line, with symbols) through the Late Miocene event is similar at A) Site 757 and B) Site 926 (western equatorial Atlantic; 3°43.148'N, 42°54.507'W). The similarity supports a global increase in IDP flux at 8.2 Myr ago. The modelled 10µm IDP flux following the Veritas collision is shown by the black curves. The model dust spike was positioned at 8.25 Myr ago and scaled to align with the ^3He peak. The fast rise time and ~1.5 Myr decay time observed in the ^3He record at both sites are well matched by the model. The inferred time of Veritas breakup is indicated (see Figure S4 for details). I/K indicates transition from illite to kaolinite clays at Site 926, a proxy for climate change.

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