RAINING MOON AND THE LATE EOCENE ASTEROID SHOWER.

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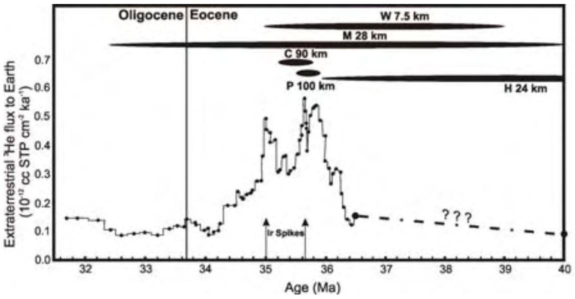
Introduction. A shower of extraterrestrial material on Earth has been proposed to explain that at least two very large and several smaller terrestrial impact structures formed simultaneously with a 2 Ma duration ^{3}He-anomaly in marine sediments, from Massignano, Italy [1]. A shower involving long-period comets was favored over an asteroid shower because: 1) the duration of the enhanced ^{3}He-flux on Earth significantly exceeded the dynamical lifetime of ~10^4 years for fine-grained dust (prevailing ^{3}He-carriers) liberated in a single asteroid disruption; 2) the ejection lifetime of long-period comets yields an event that should last about 2.5 Ma, according to Weismann's comet dynamics model; 3) the crater-forming projectiles and the ^{3}He-rich dust arrived simultaneously on Earth.

However, interpretation suffers from four major problems: 1) The nature of a brief and very intense shower of long period comets remain unclear; 2) Particles ejected from long period comets have problems to encounter Earth's atmosphere at velocities allowing to retain ^{3}He because of frictional heating during atmospheric entry; 3) The two clearly separated maxima at 35 and 35.7 Ma recorded in the ^{3}He-anomaly (**Fig. 1**) are not consistent with the Weismann's model of comet dynamics; 4) The PGE signature in the impact melts of the 100-km-diameter Popigai and 7.5-km-diameter Wanapitei craters resembles the PGE signature of L-chondrites currently falling on Earth [2-4]. Point (4) is supported by positive Cr-isotopic ratios obtained from spherules in late Eocene sediments [5]. As L-chondrites are fractionated from the original composition of the solar nebula (CI-chodrites) and formed in the inner part of the asteroid belt it is quite improbable that comets forming in the outermost regions of the Solar System would have the same composition.

A projectile shower on Earth also implies a higher impact rate on the Moon. The Moon/Earth cratering ratio is ~1/20, but contrary to Earth, even the smallest projectiles impact the lunar surface with cosmic velocities. For a typical size/frequency distribution, meter- to hundred-meter- sized projectiles outnumber km-sized projectiles by several orders of magnitude. Thus, an increased impact ejection rate of lunar material [6] and its subsequent transfer to Earth [7] could be sustained during the entire bombardment.

Helium-3 on the Moon. Compared to asteroids and comets, the Moon has a strong gravity field allowing retention of a thick regolith layer, which has accumulated ^{3}He over billions of years. Extremely high ^{3}He-concentrations of 5-50 ppb in the upper regolith layer [8] results from solar wind, solar energetic particles, and cosmogenic ^{3}He, making the Moon the largest known ^{3}He-reservoir in the inner solar system after the Sun. A relatively small amount of ~7 t of average lunar regolith (15 ppb ^{3}He = 1.22x10^{-4} cc STP/g ^{3}He) contains the annual global average of ^{3}He introduced into marine sediments during the early Oligocene [1].

Figure 1: Iridium spikes (bottom) and ^{3}He-enrichment in the sediments of Massignano [1]. The ^{3}He-anomaly is coeval with the formation of several terrestrial impact craters. Uncertainties of crater ages are displayed by the size of the ellipses: W = Wanapitei; M = Mistastin; C = Chesapeake Bay; P = Popigai; H = Haughton [23].



Moon-Earth transfer. Every impact onto the Moon results in formation of escaping ejecta mainly from the uppermost layers of regolith [6]. Depending on velocity and direction of ejection, about ~25-50% of this material reaches the Earth's upper atmosphere within a few Ma and most arrives within 10^4 years after impact ejection [7]. Thus, for a given time interval, the total mass transferred from the Moon to Earth's atmosphere is 0.25 to 2 times the integrated mass of projectiles hitting the Moon. According to our calculations ~1% of the ejected mass is subjected to shock pressures less than 10 GPa and hence are unaffected by loss of He [9], while ~10% are compressed below 20 GPa and retain more than 40% of their initial He [10]. This material contributes to the ^{3}He-flux to Earth as ^{3}He-rich lunar dust to meteorite sized fragments with some of them disrupted during atmospheric entry.

Molten impact ejecta (shock compression >50 GPa, ~30-50% of the total escaping mass) represent another efficient agent for ^{3}He to Earth. Although all ^{3}He was lost during the ejection process, dust sized particles in space environment effectively accumulate solar-wind implanted ^{3}He with saturation reached in about 10 years [11]. The orbits of the finest (0.02 to 5 µm diameter) particles are affected by non-gravitational forces including solar radiation pressure and Poynting-Robertson (PR)-drag [12]. However particles <5 µm diameter represent only a minor portion in the grain size distribution either in lunar regolith [13] or in molten ejecta [14]. The PR-drag, forcing larger (tens of µm) dust particles on geocentric orbits to spiral in towards Earth, acts in a similar time interval as the gravitational forces, i.e., 10^4 years.

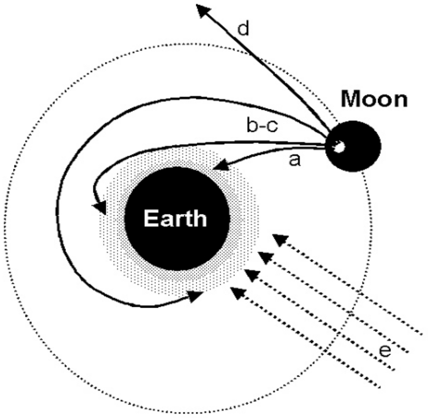


Fig.2. Projection of the Earth-Moon system onto the ecliptic plane. Solid arrows display orbits of lunar impact ejecta [7], which either travel on a direct route to Earth within a few days and encounter the Earth's atmosphere at various angles (a), or revolve around Earth on geocentric orbits for less than 1 Ma and eventually encounter the atmosphere at a low angle to the horizon with some being decelerated by aero-braking (b-c), or escape into heliocentric orbits (d).

Atmospheric heating and He-3 loses. An efficient delivery of ^{3}He-rich dust through Earth's atmosphere requires that temperatures resulting from frictional heating have to remain below the ^{3}He-release temperature of 600 °C [15]. For a particle, atmospheric entry heating is controlled by its size, mass, encounter velocity and encounter angle. Thus, lunar dust in geocentric orbits (11.1 km/s; entry angles mostly <45° to horizon [7]) delivers ^{3}He more efficiently than asteroidal (~12.1 km/s) or especially cometary (>14.1 km/s) dust in heliocentric orbits [16] – see Fig. 2.

Conclusions. The controversy of the simultaneous arrival of crater forming asteroid fragments and ^{3}He-rich particles on Earth during the late Eocene can be resolved when the Moon is considered as a target for a large number of asteroid fragments. The ^{3}He-anomaly, recorded in 36.3 to 34.3 Ma old marine sediments from Massingiano, Italy [1] could be explained by a steady "production" of impact ejected lunar material during this asteroid shower. An asteroid break-up event occurring 40 Ma ago appears to be documented by the distribution of comic ray exposure ages of L-chondrites recovered on Earth [17]. Additionally, such a break-up event might have rapidly injected abundant asteroid fragments into a resonance with short lifetimes of the resonant bodies [18-20]. A steep increase and subsequent decay in the flux of asteroid fragments to the Earth-Moon system results in a large number of lunar impacts whose temporal frequency follows the broad hump shape of the ^{3}He-anomaly, i.e. the individual impacts are essentially smeared together.

An effective transport of ^{3}He-rich lunar material to Earth via impact ejection also implies that any large lunar impact, like the formation of the ~100 km diameter Tycho crater with a suggested age of ~100 Ma [21], should be recorded by ^{3}He in marine sediments. Both the Tycho crater and the late Eocene event could justify a systematic search for fossil meteorites, similar to the one successfully performed in an Ordovician limestone quarry [22].

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