A TERRESTRIAL SYNESTIA: A NEW ENVIRONMENT FOR FORMATION OF THE MOON.
S. J. Lock¹, S. T. Stewart², M. I. Petaev³, S. B. Jacobsen¹, ¹California Institute of Technology (slock@caltech.edu); ²University of California, Davis; ³Harvard University.

Introduction: The giant impact hypothesis is the favored explanation for the formation of the Moon. However, development of chemical and isotopic predictions has been difficult, leading to substantial debate about the parameters of the impact and the process of lunar accretion. Recently, [1] discovered that high-energy, high-angular-momentum (high-AM) impacts would have transformed the proto-Earth into a synestia, a previously unknown type of planetary object, and [2] has developed a model where the Moon grew by accreting from silicate liquid within the vapor of a terrestrial synestia. The synestia model can reproduce the abundance and pattern of moderately-volatile elements in the Moon and can help explain the isotopic similarity between Earth and the Moon.

A synestia is a significantly different environment for lunar accretion than studied in previous work, which focused on accreting mass from a Roche-interior, condensate-dominated disk produced by relatively low-energy, low-AM (canonical) impacts [e.g., 3]. Important assumptions made in modeling a canonical disk are not valid in a synestia. Physical processes that are thought to be of minor consequence for the canonical disk play a significant role in the evolution of the synestia and lunar accretion. Here, we summarize the formation of the Moon within a terrestrial synestia, highlighting the advantages of the model and differences with previous work.

What is a synestia? There is a thermal limit (well below thermal escape) for any rotating planet. When a planet is partially vaporized, it expands in volume. At a critical level of thermal energy, the rotation velocity of the expanded equator intersects the Keplerian orbital velocity. Beyond this point, the mass cannot form a corotating, hydrostatic body, and the equatorial region expands into a viscously-spreading disk-like region. Above this corotation limit, the body becomes a synestia. The distribution of mass and angular momentum within a synestia depends on the process that formed it, leading to a range of shapes and sizes.

Synestias can be produced by giant impacts with only slightly larger energy and AM than the canonical impact. The internal structure of a synestia typically consists of a corotating, inner region and a disk-like, outer region, with the transition point located up to ~2R_{Earth} away from the rotation axis for Earth-like compositions. The angular velocity and thermal state are continuous between the two regions of a synestia, whereas the boundary between a planet with a silicate vapor atmosphere and a condensate-dominated disk has a strong discontinuity in both parameters. In the disk-like region of a synestia, the pressure-gradient force is comparable to the centrifugal force and the vapor orbits with strongly sub-Keplerian velocities. In a canonical disk the pressure-gradient force is small.

Giant impacts that form Earth-mass bodies also deposit substantial thermal energy and, in most cases, there is no liquid surface in the post-impact planet or synestia. The silicate transitions smoothly from a supercritical fluid to vapor with decreasing pressure. Up to 10s wt% of silicates in synestias are either vapor or supercritical fluid. Due to the low density of vapor and a strong centrifugal force, synestias can extend well beyond the Roche limit. In some cases, the initial thermal structure of synestias permit stable liquid-vapor mixtures only beyond the Roche limit. In contrast to a condensate-dominated disk where the phase boundary constrains the entire disk structure [e.g., 4], each synestia has a distinct thermal structure.

Synestias are rapidly evolving objects: Synestias continuously evolve by viscous spreading and thermal evolution. The photosphere radiates at ~2300 K, a value buffered by the silicate vapor curve. Rapid cooling drives vapor condensation, reducing the pressure support and causing the synestia to contract. The lower surface densities at larger cylindrical radii lead to condensation and contraction of the outer regions while the inner regions remain vaporous.

Over the timescale of lunar accretion (10s years), several lunar masses of magma rain falls from the photosphere into the synestia. The droplets experience strong gas drag from the sub-Keplerian vapor and spiral towards the rotation axis, traveling inwards as much as 10^5-10^6 m before vaporizing. As droplets fall, they transfer AM to the vapor. The transport of AM and mass inwards by condensates will be partially counteracted by increased pressure from vaporizing droplets and viscous spreading as the structure adjusts to the evolving AM and mass distribution. Within a synestia, the radial transport of AM and mass by falling condensates is an important process.

Viscous spreading is the principal AM and mass transport mechanism in canonical disks. However, the origin and magnitude of the viscosity, the relative time scales for cooling and viscous spreading, and the transfer of mass and AM between the disk and the planet’s extended atmosphere are all uncertain. Both the boundaries between the corotating and disk-like regions of a synestia and between a planet’s vapor atmosphere and a canonical disk are dynamic and can evolve in location and angular velocity with transport of mass and AM. The magnitude of resonant torques, such as Lindblad resonances, are unknown in a synestia as current formulations [e.g., 3] assume a thin disk.
Clarifying the physical processes that govern mass and AM transport following all giant impacts is an important focus for future work.

**The Moon forms within the synestia:** Synestias can extend far beyond the Roche limit. The Moon accretes within the synestia, surrounded by 10s bars of bulk silicate Earth vapor. This environment is a major feature of the synestia model because it explains the chemical relationships between Earth and the Moon.

The impact injects some liquid debris into the synestia beyond the Roche limit, and this debris accretes quickly to form moonlets. The Moon grows by accreting moonlets and some of the falling condensates. The lunar composition is determined by chemical equilibrium between the liquid condensates and the synestia vapor. [2] showed that the lunar moderately volatile element abundances can be quantitatively reproduced by liquid-vapor equilibration of bulk-silicate Earth system at the pressures in the midplane of a synestia (10s bars) and temperatures buffered by the onset of silicate vaporization. The vapor pressures in a synestia are much higher than in a canonical disk, and equilibration at lower pressures does not reproduce the lunar composition [2].

While [2] demonstrated that the lunar composition can be approximated by equilibration at a single pressure and temperature, the history of lunar material within a synestia is more complex. There is continuous chemical and thermal exchange between the vapor and condensates, and the dynamic environment may inhibit chemical exchange from occurring at perfect equilibrium. Small isotopic fractionations may arise from kinetic or mass-dependent processes. When the terrestrial synestia cools to the point that it contracts within the lunar orbit, the Moon emerges as a separate body. The synestia and the Moon then follow different chemical and thermal evolutionary paths. The terrestrial synestia becomes a normal planet in 100s-1000s years by cooling along the silicate vapor curve to form a magma ocean surface. The Moon accreted at the modest pressures and high temperatures in the synestia and began to solidify after separation. The lunar composition is strongly depleted in volatile elements compared to the synestia. Thus, at the time of separation, the $f_{\text{O}_2}$ of lunar material differs from that of the synestia that will later form the terrestrial mantle. The pressures and temperatures at the end of core formation are also very different in the two bodies. The fact that the present-day lunar and terrestrial mantles have different $f_{\text{O}_2}$ does not rule out formation of the Moon from terrestrial material.

**Requirements for lunar origin in a synestia:** In general, giant impacts have been able to emplace more than a lunar mass of iron-depleted material into orbit. The current challenges for lunar origin are primarily (i) reproducing the chemical and isotopic composition of the Moon and its relationship to Earth through an improved understanding of thermophysical and dynamical processes during impacts and lunar accretion and (ii) exploring dynamical pathways to the present AM of the system and the inclination of the lunar orbit. The synestia model is an alternative pathway to create the Earth-Moon system that does not impose the assumption that the Moon-forming event set the present-day AM. For example, a plausible high-energy, high-AM giant impact that imparted a high obliquity could form the Moon in a synestia [2] and produce a system that then evolved to the present AM and lunar inclination [5].

Formation of an Earth-mass synestia requires an impact that leaves the system with more than about 1.5 times the present-day AM. [1] demonstrated that most Earth-like planets experience several impacts during accretion with sufficient energy to produce synestias and, given the expected AM distribution [6], most of these impacts would form synestias. Thus, synestias are a common feature of terrestrial planet formation.

Many different impact configurations (mass ratio, velocity, angle) can produce potential Moon-forming synestias. The formation of a suitable synestia does not require any specific pre-impact rotation of the proto-Earth or mass of impactor. Different impact conditions yield synestias with a wide variety of thermal, AM and mass distributions, and [2] found example potential Moon-forming synestias formed by collisions between: non-rotating half-Earth mass bodies; non-rotating 0.75 and 0.3 Earth-mass bodies; and less than Mars-mass bodies and an already rapidly-rotating proto-Earth.

In general, high-energy and high-AM impacts mix material from the two bodies to a greater degree compared to the canonical case. The W similarity between Earth and the Moon requires that lunar and terrestrial mantle material originated from a common source [e.g., 7]. The apparent degree of mixing in current models of synestia formation and evolution appear to satisfy this requirement [2]. More work on mixing and lunar accretion within a synestia is necessary to determine which structures are most favorable for lunar origin. Finally, the feasibility of any high-AM model is contingent on transfer of AM away from the Earth-Moon system during lunar tidal recession and producing an inclined lunar orbit [e.g., 5].

**Conclusion:** Forming the Moon from a synestia is a new pathway to the Earth-Moon system. In general, results and techniques from previous work on the lunar disk cannot be directly applied to a synestia.