THE POST-IMPACT STATE OF THE MOON-FORMING GIANT IMPACT: FAVORABLE ASPECTS OF HIGH-ANGULAR MOMENTUM MODELS S. J. Lock[1], S. T. Stewart[2,1], Z. M. Leinhardt[3], M. Mace[3] and M. Ćuk[4], [1]Harvard University, Department of Earth and Planetary Sciences, Cambridge, MA 02138 (slock@fas.harvard.edu); [2]University of California Davis, Department of Earth and Planetary Sciences, Davis, CA, USA; [3]University of Bristol, School of Physics, Bristol, U.K; [4]The SETI Institute, Mountain View, CA, USA.

Introduction: In the giant impact model, the Moon formed from a circumterrestrial disk of droplets and vapor. The canonical impact is a Mars-sized body impacting the Earth at a velocity and angle constrained by the angular momentum (AM) of the present Earth-Moon system [e.g. 1]. Recently, however, in an attempt to solve the problem of the isotopic similarity of the Earth and Moon, new high-AM impact scenarios have been proposed [2, 3]. The aftermath of these high-AM impacts is fundamentally different than the canonical post-impact state. We contrast the post-impact states and explore favorable aspects of the high-AM cases that could allow for more efficient moon formation and mixing of material.

A Fundamentally Different Post-Impact State: Previous studies of the canonical disk have treated the disk either as N-body [e.g. 4, 5], a vapor and fluid mixture [e.g. 6, 7] or a combination of the two [8]. A common cartoon of the disk is shown in figure 1A with a mixed liquid and vapor disk with a condensed layer in the mid-plane. There is a discontinuity between the planet's atmosphere and the disk in entropy and rotational velocity (figures 2, 3A). The moon is formed by the unstable condensed layer transferring AM and raising the orbit of moonlets beyond the Roche radius, a_R. The transfer of AM to the Moon is compensated by disk material spreading inwards and accreting onto the Earth.

The high-AM impacts are also high energy. After the impact, the mantle, atmosphere and disk (MAD) form a continuous supercritical fluid and vapor body (figures 1B, 2, 3); i.e., there is no discontinuity in either entropy or rotational velocity between the planet and disk. The MAD is both rotationally and pressure supported and the liquid-vapor phase boundary is only crossed at the outer boundary. In the simplest case, the MAD extends outside a_R and the moon is formed by droplets condensing and coalescing into moonlets. In-falling droplets encounter higher pressures and temperatures and vaporize. Mass is resupplied beyond a_R by the pressure gradient. The AM for the moon is acquired by reducing slightly the spin-period of the planet.

It is a common misconception that a fully vapor disk will hydrodynamically escape [e.g., 9]. However the vapor in the circumterrestrial disk is condensable, unlike the case of hydrogen-dominated astrophysical disks, and does not escape. Moonlets form by partial condensation of a vapor of BSE composition [10].

Mixing the MAD Planet: Moonlets condense at the edge of the MAD on a timescale of >~years with the whole MAD cooling in ~100 yrs. This is much faster than the mixing time of the MAD. The MAD therefore efficiently equilibrates terrestrial and lunar material without most of the issues raised for the canonical disk [11, 12]. With equilibration, the phase space of successful moon forming impacts increases and the lower probabilities associated with the original high-AM impact scenarios is alleviated. The high-AM cases may also lead to more efficient moon formation (e.g., a larger mass moon) as the dynamics within the MAD could transfer AM from the interior and supply mass beyond a_R.

Conclusion: We have found that the post-impact state is fundamentally different between high-AM and canonical moon-forming impact scenarios. The high-AM events form a continuous pressure and rotationally supported mantle, atmosphere and disk (MAD) with no dynamic and thermodynamic discontinuity between the disk and planet as there is in the canonical case. The MAD is efficiently mixed, leading to equilibration of terrestrial and lunar material. Furthermore the ability for lunar material to gain AM via slowing the rotation of the planet could allow for more efficient moon formation. In this model the moon is a partial condensate from a BSE vapor [10].

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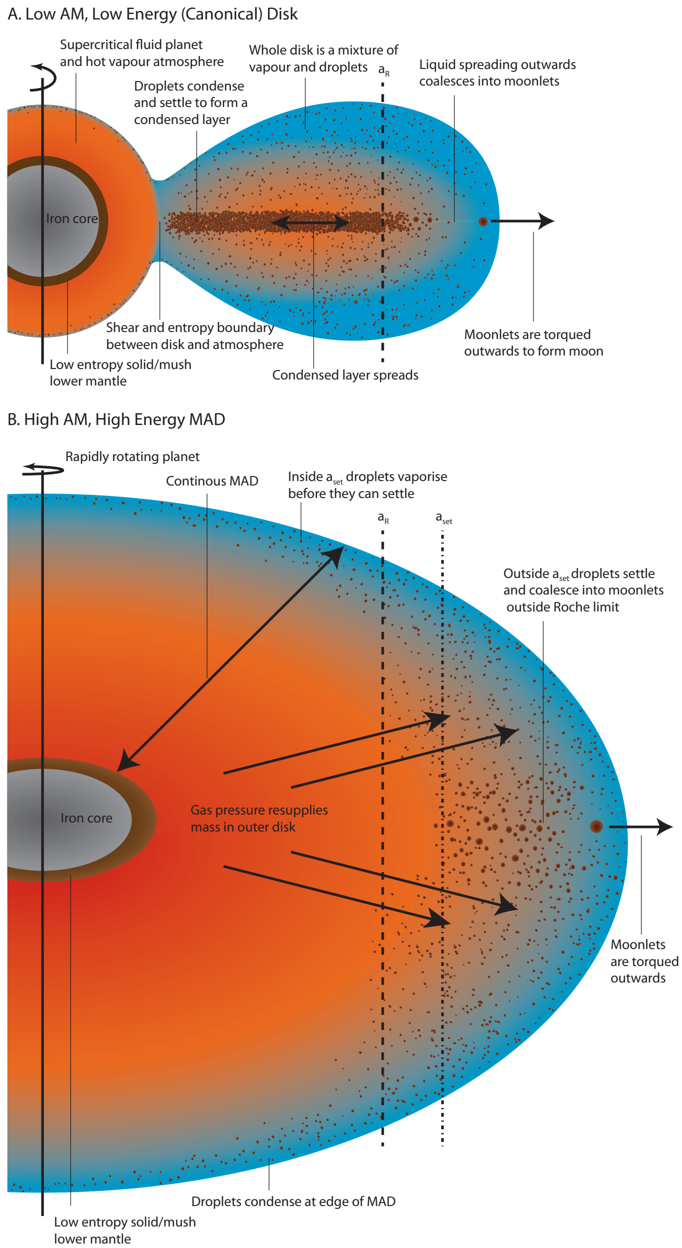
Figure 1: (right) Cartoons of the lunar disk in the canonical scenario (A) and high-AM cases (B). (A) The traditional model of a lunar disk with a condensed layer and a discontinuity between planet and disk. (B) The continuous MAD structure formed in the high-AM cases. Here, moonlets condense from vapor outside a_R. a_{set} is the radius at which droplets can settle to the midplane of the MAD.



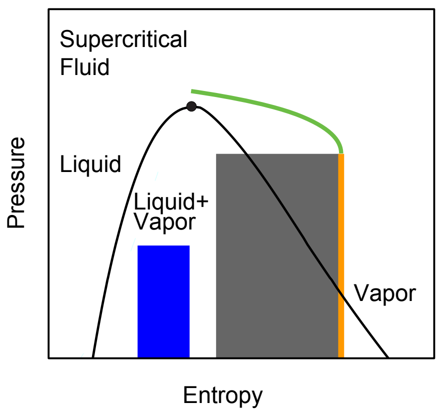


Figure 2: Schematic pressure-entropy phase space occupied by the post-impact planet. For both canonical and high-AM events, the mantle and atmosphere span supercrical fluid to vapor (green). The entropy ranges for the canonical disk are discontinuous with the planet (blue) and continuous with the high-AM impact scenarious (orange from [2] and grey from [3]). The black line is the liquid-vapor phase boundary for forsterite [13]. Black dot marks the critical point: 7900 K, 0.45 g/cm^3, 0.3 GPa [13].

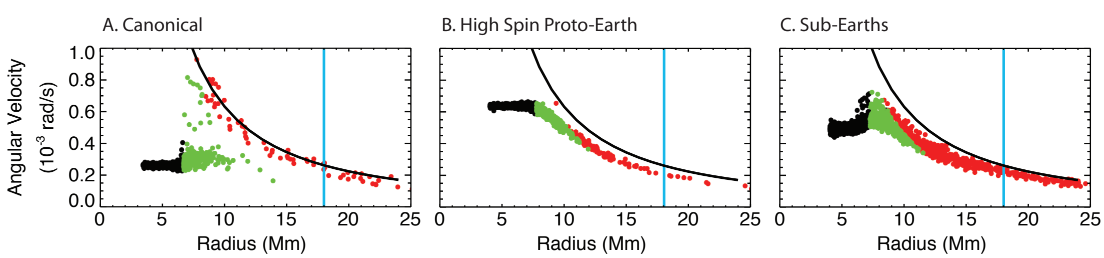


Figure 3: Angular velocity profiles in the midplane (post-impact) for A) a canonical impact [1] B) an impact with a fast-spinning proto-Earth [2] and C) a sub-Earths collision [3]. Colors: black points are mantle with density >1 g/cm^3; green points are 'atmosphere' (i.e., they are vapor but do not have enough AM to remain in orbit if thermal pressure were removed); and red points are in the 'disk' (i.e., they have enough AM to stay in orbit if thermal pressure were removed). The black lines indicates a Keplerian orbit. The blue lines mark the Roche radius, a_R.