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Volatile loss and atmospheric formation: Planetesimals, Moons, and Earths

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The timing and mode of delivery of volatiles, including water and carbon compounds, to the Earth and other terrestrial planets is the subject of multiple hypotheses and little agreement. Theory and modeling of planetary accretion processes indicates that terrestrial planets are built by giant accretionary impacts with planetesimals, bodies that have likely internally differentiated into a core and mantle before accretion. The path of volatile addition to the final planet, therefore, passes first through accretion and differentiation in planetesimals with lower mass.

Planetesimals that accrete before ~2 Ma after the formation of calcium-aluminum inclusions will likely heat and partially melt from the inside from the effects of short-lived radioisotopes. This heating event will mobilize volatiles toward the planetesimal surface and create an interior with a roughly radial gradient in both oxidation state and volatile content.

Late, giant accretionary impacts between planetesimals and planetary embryos likely result in partial but not complete devolatilization, and form multiple magma oceans of some depth in young rocky planets. Models of magma ocean solidification that incorporate water, carbon, and other incompatible volatile elements in small amounts predict a range of first-order outcomes important to planetary evolution.

Initial planetary bulk composition and size determine the composition of the earliest degassed atmosphere. On low-volatile, small bodies like the Moon, the cold radiative surface may produce a volatile cold trap within the crust, storing volatiles for later volcanic fire-fountaining of the otherwise dry interior magmas.

On larger bodies with free-surface magma oceans, the early atmosphere appears in a rapid burst at the end of solidification, determined by the ability of nucleating bubbles to reach the surface. Larger planets will have briefer and more catastrophic atmospheric degassing during solidification of any magma ocean.

This early atmosphere is sufficiently insulating to keep the planetary surface hot for millions of years. Depending upon the atmospheric composition and temperature structure these hot young planets may be observable from Earth or from satellites.

Keywords: water, planetary formation, accretion, planetesimal