Impacts and the Delivery & Erosion of Volatiles

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The Origins of Volatiles in Habitable Planets: The Solar System & Beyond

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Exoplanet Densities

Data from Weiss & Marcy 2014, Juntof-Hutter et al. 2015, Barros et al. 2015
Envelope Accretion:

Accretion limited by cooling (e.g. Inamdar & Schlichting (2015), Lee & Chiang (2015))

\[ f \approx 0.02 \left( \frac{M_c}{M_\odot} \right)^{0.8} \left( \frac{T_{eq}}{10^3 \text{ K}} \right)^{-0.25} \left( \frac{t_{\text{disk}}}{1 \text{ Myr}} \right)^{0.5} \]

\[ T(R_e) \sim 5 \cdot 10^3 \text{ K} \]

\[ \rho_d \sim 10^{-6} \]

\[ \rho_{\text{reb}} \sim 10^{-4} \]

\[ \rho(R_e) \sim 10^{-2} \]

\[ t = t_{\text{dyn}} \sim 1 \text{ day} \]

\[ t_{\text{dyn}} < t < t_{\text{disk}} \]

\[ t = t_{\text{disk}} \sim 10 \text{ Myr} \]

\[ \text{Ginzburg, Schlichting & Sari (2016)} \]
Late Collisions & Kepler Multiple Planet Systems

Fig. 1.— Histogram showing the period ratios of Kepler planet candidates residing in multiple planet systems as of January 2013. The location of dominant mean motion resonances are drawn as dashed black lines for comparison. There is a significant excess of planet pairs with period ratios close to mean motion resonances. However most planets do not reside in or close to resonances.

Cossou et al. 2014

Izidoro et al. 2017

4175 Planetary Candidates

1218 Planets in Multi-Planet Systems

Giant Impacts & Atmospheric Mass Loss

1) High-velocity impactor hits the surface of the planet

2) Its velocity is sharply decelerated and its kinetic energy is rapidly converted into heat and pressure resulting in something analogous to an explosion (Zel'dovich & Raizer, 1967).

**Mechanical part**

i) The impact launches a strong shock.

ii) The shock propagates through the planet causing a global ground motion.

iii) This ground motion launches a shock into the atmosphere, which can lead to significant atmospheric loss.

**Thermal part**

i) The impact heats the core.

ii) The core exchanges heat with the envelope.

iii) The envelope expands and will be partially or fully lost.
Envelope loss due to Giant impacts

Single collision can easily reduce the envelope-to-core-mass ratio by factors of two or more

See also Liu et al. 2015
Single collision can easily reduce the envelope-to-core-mass ratio by factors of two or more, leading to increase in observed mean density by factors of ~2-6.


Small number of Giant Impacts can give rise to a large diversity in exoplanet densities.

Especially attractive explanation for diverse bulk densities observed in multiple planet systems: e.g. Kepler-11, Kepler-20, Kepler-36, Kepler-48, and Kepler-68.
Point-like explosion on the surface, where a mass equal to the mass of the impactor propagates isotropically into a half-sphere with velocity of order the escape velocity.

Planetesimal Impacts

1) Only eject atmosphere locally, $h/2R$, – but numerous small impacts

2) Atmosphere is ejected where its mass per unit solid angle is less than of the ejecta, $m_{\text{imp}}/2\pi$. (e.g. Melosh & Vickery 1989, Zahnle et al. 1990, Schlichting et al. 2015)
Atmosphere is ejected only where its mass per unit solid angle is less than of the ejecta, \( m_{\text{imp}}/2\pi \).

**Smallest Impactor Size that can remove any atmosphere:**

\[
r_{\text{min}} \approx \left( \frac{\rho_0}{\rho} \right)^{1/3} h \sim 1\text{km}
\]

**Smallest Impactor Size that can remove all atmosphere above tangent plane:**

\[
r_{\text{cap}} \approx \left( \frac{\rho_0}{\rho} \right)^{1/3} (hR)^{1/2} \sim 25\text{km}
\]
Earth’s atmosphere may have resulted from equilibrium between atmospheric erosion and volatile delivery from planetesimal impacts.
Atmospheric Mass Loss Efficiency for current Earth

Planetesimal impacts likely dominated the atmospheric mass loss over the formation history of the terrestrial planets.

Schlichting et al. 2015
Regime 1) dominates for $q>3$, Regime 2) dominates for $1 < q < 3$
Volatile delivery and atmospheric erosion due to planetesimal impacts

Whether or not the Earth’s atmosphere is eroded or grown during the late accretion phase depends critically on the initial volatile content of the mantle at the end of the magna ocean phase after the last giant impact (Elkins-Tanton 2008, Black et al. 2012) and the volatile content of the impactors.
Summary

- Planetesimal impacts likely dominated the atmospheric mass loss over the formation history of the terrestrial planets. For complete loss need planetesimals: $M=M_{\text{atmos}}$, Giant Impacts: $M=M_{\text{core}}$

- 0.1-0.5% of Earth masses in small impactors, which is about the mass inferred for the late veneer, can erode the entire Earth's atmosphere. Atmospheric erosion is a runaway process.

- Earth’s early atmosphere could have resulted from equilibrium between atmospheric erosion and volatile delivery from planetesimal impacts + outgasing. Planetsimals dominate the atmospheric loss, Giant Impacts dominate the outgasing.