System-level fractionation of carbon from disk and planetesimal processing

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Lichtenberg & Krijt (2021), ApJL 913, L20 | exoplanet-talks.org/talk/358
Water + carbon depletion during planet formation

The World’s Water

Water, carbon, and other elements are depleted during planet formation.
Water + carbon depletion during planet formation
(C/H) ~ (O/H) ~ (N/H) ~ 10^{-4}

\[
\frac{\text{dust}}{\text{gas}} \approx 1\%
\]

"t=0"
Molecular Cloud Core

\[t \approx 10^{4-5} \text{ yr}\]
A protostar + disk form

\[t \approx 10^{5-6} \text{ yr}\]
Pré-main-sequence star + disk

\[t \approx 10^{6-7} \text{ yr}\]
Massive planets form and open gaps

\[t > 10^7 \text{ yr}\]
Gas clears and planetary system emerges

\[(\text{CO/H}_2)_{\text{gas}} \approx 10^{-4}\]
**Condensation Temperature**

- ~1400 K
- ~500 K
- <150 K
- Unknown

\[ \frac{\text{dust}}{\text{gas}} \approx 1\% \]

**“t=0”**

Molecular Cloud Core

\[ t \approx 10^{4-5} \text{ yr} \]
- A protostar + disk form

\[ t \approx 10^{5-6} \text{ yr} \]
- Pré-main-sequence star + disk

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- Massive planets form and open gaps

\[ t > 10^7 \text{ yr} \]
- Gas clears and planetary system emerges

**(Zhang, Schwarz, and Bergin 2020)**

\[ (C/H) \sim (O/H) \sim (N/H) \sim 10^{-4} \]

*In the gas, in the warm molecular layer*

**(Öberg & Bergin 2021)**

- O budget
- C budget
- N budget

**Gas CLEARs and planetary system emerges**
Sequestration of CO ice on pebbles in the midplane?

Reduced gas-phase CO/H$_2$

Elevated gas-phase CO/H$_2$

Sequestration of CO ice on pebbles in the midplane?
From Pebbles to Planetesimals: Where and When?

Primordial planetesimal composition set by pebble composition at time & location of pebble cloud collapse.

(Figure: P. Armitage)
Thermal evolution from radiogenic heating

Time after Solar system formation [Myr]

- $^{26}\text{Al}$ ($t_{1/2} = 0.716 \text{ Ma}$)
- $^{60}\text{Fe}$ ($t_{1/2} = 2.62 \text{ Ma}$)
- $^{40}\text{K}$ ($t_{1/2} = 1400 \text{ Ma}$)
- $^{235}\text{U}$ ($t_{1/2} = 704 \text{ Ma}$)
- Total heating

Planetesimal formation
Thermal evolution from radiogenic heating

- Planetesimal formation

**Radiogenic heating, log_{10} [W/kg]**

- \( ^{26} \text{Al} \) (\( t_{1/2} = 0.716 \text{ Ma} \))
- \( ^{60} \text{Fe} \) (\( t_{1/2} = 2.62 \text{ Ma} \))
- \( ^{40} \text{K} \) (\( t_{1/2} = 1400 \text{ Ma} \))
- \( ^{235} \text{U} \) (\( t_{1/2} = 704 \text{ Ma} \))
- Total heating

**Time after Solar system formation [Myr]**

0  2  4  6  8  10  12  14  16  18  20
Compositional evolution from radiogenic heating
Volatile content of evolved planetesimals

A: Young disk

- $H_2O$
- $CO_2$
- $CO$

- Decreasing pressure & temperature

Temperature and pressure gradients: the locations of major icelines

B: Dust and disk processing

C: Planetesimal formation

D: Planetesimal evolution

- Decreasing pressure & temperature
- Dust coagulation leads to settling and inward radial drift
- Ongoing chemistry and pebble formation and radial drift alter the volatile abundances

Primordial planetesimals form via the streaming instability, inheriting the volatile and radionuclide abundance of the pebbles

- Planetesimals that are efficiently heated by short-lived radionuclides lose a significant fraction of their volatiles

Temperature and pressure gradients: the locations of major icelines

E: Ice content of solids in the disk midplane

- $CO$
- $CO_2$
- $H_2O$

- $t = 0$
- $t = 1$ Myr
- $t = 2$ Myr
- $t = 4$ Myr

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Volatile content of evolved planetesimals

A: Young disk

B: Dust and disk processing

Decreasing pressure & temperature

Dust coagulation leads to settling and inward radial drift

Ongoing chemistry and pebble formation and radial drift alter the volatile abundances

Temperature and pressure gradients: the locations of major ices

CO

CO₂

H₂O

Primordial planetesimals form via the streaming instability, inheriting the volatile and radionuclide abundance of the pebbles

Planetesimals that are efficiently heated by short-lived radionuclides lose a significant fraction of their volatiles

Temperature and pressure gradients: the locations of major ices

Ice content of solids in the disk midplane

Ice content of solids in the disk midplane

Evolved planetesimals

Ice content of solids in the disk midplane

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Ice content of solids in the disk midplane
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E: Ice content of solids in the disk midplane
- Temperature and pressure gradients the locations of major ices

F: Ice content of solids in the disk midplane
- Decreasing pressure & temperature
- Dust coagulation leads to settling and inward radial drift
- Ongoing chemistry and pebble formation and radial drift alter the volatile abundances

G: Ice content of solids in the disk midplane
- Temperature and pressure gradients the locations of major ices
Volatile content of evolved planetesimals

A: Young disk

- Temperature and pressure gradients: the locations of major ices

B: Dust and disk processing

- Ongoing chemistry and pebble formation and radial drift alter the volatile abundances

C: Planetesimal formation

- Primordial planetesimals form via the streaming instability, inheriting the volatile and radionuclide abundance of the pebbles

D: Planetesimal evolution

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Large planetesimals and/or those with more $^{26}$Al can lose >90%!
Final volatile (in this case CO) content of evolved planetesimals can be very different from that of microscopic dust grains at \( t=0 \), depending sensitively on radial location & both disk processes and thermal evolution of planetesimals.

**Volatile content of evolved planetesimals**

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### Cosmic ionisation rate

- \( \zeta_{CR} = 10^{-17} \, \text{s}^{-1} \)
- \( \tau_{PF} = 0 \, \text{Myr} \)
- \( \tau_{PF} = 3 \, \text{Myr} \)

### Plot A

- Log-log plot of CO content (%) vs. \( r/\text{au} \)
- \( \zeta_{CR} = 10^{-17} \, \text{s}^{-1} \)
- \( \tau_{PF} = 0 \, \text{Myr} \)
- \( \tau_{PF} = 3 \, \text{Myr} \)

### Plot B

- Log-log plot of CO content (%) vs. \( r/\text{au} \)
- \( \zeta_{CR} = 10^{-18} \, \text{s}^{-1} \)
- \( \tau_{PF} = 0 \, \text{Myr} \)
- \( \tau_{PF} = 3 \, \text{Myr} \)

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Exo-comet compositions in Gas-rich Debris Disks

Collage of debris disks as seen by ALMA in sub-mm continuum (Wyatt 2019)
Comparing model predictions of planetesimal volatile content to observational constraints (for example from gas-rich debris disk) will shed light on the planetesimal formation process (Matrà et al. 2017).

Evolved planetesimals vs. exo-comets

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1. Molecules & microscopic dust
   - freeze out
   - fragmentation
   - dust drift
   - grain surface chemistry

2. Pebble growth & dynamics
   - collisions
   - vertical settling
   - radial drift

3. Planetesimal formation
   - Planetesimals form from local dust composition
   - CO ice line (~20 K)
   - H₂O ice line (~170 K)
   - Temperature and pressure decrease with distance
   - Drifting pebbles supply inner disk with gas-phase volatiles
   - Elevated C/H and O/H?
   - Diffusive transport

4. Planetesimal thermal evolution
   - Volatile outgassing
   - Heating, melting & mixing
   - Chemistry largely “inherited” from natal Molecular Cloud
   - Accretion of “dry” materials… vs. accretion of “wet” materials
   - Dust grains “reset” in hot inner parts
   - System-level fractionation of carbon from disk and planetesimal processing

5. Delivery to terrestrial planets
   - Accretion of icy materials… vs. accretion of “wet” materials
   - Volatile content of forming planets is shaped by the composition of pebbles and planetesimals

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