Water from Clouds to Disks

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see van Dishoeck PPVI chapter
Water Formation before Star Birth

Water vapor in emission - arising in dense ($n > 10^5 \text{ cm}^{-3}$) gas

Gas abundance is low/ice is high - water (and O) is in ice

Current models (Visser+2009) suggest water ice supplied to disk is unaltered.

Young disk is least understood stage

Caselli et al. 2012, Keto+ 2015
Hollenbach+ 2009, Klotz+ 2008

Whittet et al. 1983
Gibb+ 2004, Boogert+ 2013
Deuterium Fingerprint

Altweegg+ 2014
Deuterium Chemistry

- Deuterium fractionation for water primarily powered by one reaction:
  \[ \text{H}_3^+ + \text{HD} \leftrightarrow \text{H}_2\text{D}^+ + \text{H}_2 + \Delta E \]

- Requires 2 ingredients
  1. Source of Ionization
  2. Low temperatures (< 30 K)

- Most disk models assume initial D/H in water is high and it is lowered by mixing between hot and cold gas.

- Two potential environments - dense pre-stellar core or dense outer disk.
Ionization in Disks:
The culprits

- Radionuclides
- Thermal
- X-rays
- ISRF
- Cosmic Rays

Cleeves
Ionization in Disks: The culprits

- ISRF
- Cosmic Rays
- Radionuclides
- X-rays
- Thermal

Meteoritic Record
Excess of $^{26}\text{Mg}$ points to large quantities of $^{26}\text{Al}$.
Ionization in Disks: The culprits

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Stellar UV

Photon energy (keV)

Count rate (cts s$^{-1}$ keV$^{-1}$)

SU Aur
V410 Tau
V773 Tau
HD 283572
Ne X
Mg XII
Si XIV
S XVI
Mg XI
Si XIII
S XV
Fe XXV
Fe XVII
O VIII

Telleschi+2007
Herczeg+2002,2004
Cleeves
Disk Ionization

Cleeves, Adams, and Bergin 2013
D/H Ratio in Water

Cleeves et al. 2014
Under assumption that cosmic rays are excluded (confirmed in TW Hya; Cleeves et al. 2015) - then some of solar system water was formed ~1 Myr before Solar birth in the pre-stellar core.
Oxygen in TW Hya

Debes et al. 2013

TW Hya Disk
HST NICMOS/NIC2
F171M+F180M+F222M

Disk
Location of Star
Coronagraphic Spot
Gap

15 billion miles
160 AU
3"

N
E
Oxygen in TW Hya

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Warm water

Zhang et al. 2013

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Compassographic Spot
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Flux (Jy)

Wavelength (μm)
Oxygen in TW Hya

Debes et al. 2013

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Hogerheijde et al. 2011

cold water

Debes et al. 2013

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Zhang et al. 2013

Column density (cm⁻²)

R (AU)

NIRSPEC
Spitzer
PACS
HIFI+ALMA

Inner disk
Outer disk
Gas
Water
Thermo-Chemical Model
Du & Bergin 2014

- adopt physical model of gas and dust distribution - fit the dust SED
- solve (2D) dust radiation transfer
- propagate UV (continuum/Ly $\alpha$) and X-ray photon - solve in concert with $\text{H}_2$ & $\text{H}_2\text{O}$ (Bethell & Bergin 2011)
- solve coupled chemistry (> 500 species and > 5000 reactions) and thermal physics
- predict emission lines (non-LTE approx)
- include HD (Bergin et al. 2013) to constrain mass
Constrained Disk Chemistry

- Re-examine all TW Hya Data with knowledge of HD
- Use new thermochemical model (Du and Bergin 2014)

\[ C^+ \, ^2P_{3/2} - ^2P_{1/2} \]
\[ O \, ^3P_1 - ^3P_2 + ^3P_0 - ^3P_1 \]
CO 2-1, 3-2, 6-5, 10-9, 23-22
\[ ^{13}\text{CO} \, 2-1, C^{18}O \, 2-1 \]
HD 1-0 (detection) + HD 2-1 (limit)
H2O (Spitzer/IRS, Herschel/PACS, Herschel/HIFI)
OH (Spitzer/IRS)

Du, Bergin, & Hogerheijde 2015
Two models

1. O + C depleted beyond snow lines
2. O + C undepleted

Main elemental carriers -

O: H$_2$O (ice and gas), CO, O I

C: CO (ice + gas), organics

Du, Bergin, & Hogerheijde 2015
Water Abundance
undepleted $O_2$

Du, Bergin, & Hogerheijde 2015
Water Abundance
undepleted $O_2$
Water Abundance
undepleted O

H$_2$O

I. Hot water chemistry and ice evaporation - balanced by exposure to stellar irradiation
Water Abundance
undepleted O

1. Hot water chemistry and ice evaporation - balanced by exposure to stellar irradiation

2. Water ice dominated - beyond snow line (4 AU for TW Hya) no ice evaporation in midplane
Water Abundance

undepleted O

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3. Photodesorption layer - UV radiation must be present
Du, Bergin, & Hogerheijde 2015
Water beyond the snow line..

\[
\begin{align*}
\text{[O I] 63 \mu m} & \quad E_u = 228 \text{ K} \\
\text{H_2O 538 \mu m} & \quad E_u = 61 \text{ K} \\
\text{H_2O 269 \mu m} & \quad E_u = 53 \text{ K} \\
\text{H_2O 179 \mu m} & \quad E_u = 114 \text{ K}
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Du, Bergin, & Hogerheijde 2015
Water Abundance

deprecated O

- Need to remove water ice from layers with UV (i.e. reduce photodes. efficiency)
- Also in 5-20 AU need to reduce available O to form water via gas phase reactions

Du, Bergin, & Hogerheijde 2015
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Du, Bergin, & Hogerheijde 2015, in prep.
Systematic Effect

- Cold water emission survey
  - 7+ systems surveyed - no detections beyond TW Hya and HD100546 (Du et al., in prep.)

- O I less emissive compared to continuum in sample of 21 transition disks (Keane et al. 2014)

- \(^{18}\)O/HD ratio in TW Hya gives CO/H\(_2\) \(< < 10^{-4}\) (Favre et al. 2013)

- \(\text{C}^+\) detected in 27% out of 47 T Tauri stars surveyed by Herschel -- all have UV excess (Dent et al. 2013)
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Where are the volatiles?
Likely trapped in pebbles or larger bodies in the midplane. Need reduced return of micron sized ice coated grains that can be lofted to the surface.
Summary

- Water is formed as ice in pre-stellar stage, with D signature implanted at this time.
- Cosmic rays may not be present in the disk which has implications for disk chemistry and physics.
- Detection of HD combined with observations of volatiles suggest presence of hidden reservoirs -> pebbles.
- Effect of missing volatiles in upper layers is systematic — we are tracing the carriers of volatiles to forming worlds.
- Timescale of ice sequestration/volatile depletion is intertwined with gas dispersal timescale and gas mass estimates from CO.