THE HERSCHEL VIEW ON WATER IN STAR AND PLANET FORMATION

Edwin (Ted) Bergin
University of Michigan
• What happens to interstellar water during collapse and disk formation?
• How are planets formed?
• Does the chemical composition of planets today relate to it birth? If so what might it mean?
• Is an Earth-like world composition a pre-ordained outcome?
• Life…..

Amazing landscape of exoplanet discovery and characterization (ground and space).

Herschel was key to laying the ground work for today’s understanding - we are not done!!!!

van Dishoeck, Bergin, Lis, & Lunine 2014 (PPVI)
Open time programs, i.p.
WILL, DIGIT, Cygnus, ATLASGAL

\[ \sim 1\text{-}10 \quad \sim 100\text{-}1000 \]

Low-
Intermediate-

\sim 80 \text{ sources}
Doubled with OT programs

-> Joe Mottram's talk

Prestellar 0
Class 0

\sim 10^4\text{-}10^5 \ L_{\odot}
High-mass
Mass

Class 1

\sim 0.4 \ \text{Myr}
Disks

\sim 2 \ \text{Myr}
Time

Lars E. Kristensen
ICES ARE ABUNDANT AND COMMON!

Ices can contain significant fraction of heavy elements (but perhaps not all oxygen).

Boogert, Pontoppidan et al. 2008,
Öberg et al. 2011
Boogert et al. 2015, ARAA

Image: S. Bottinelli
Water is emitting from gas with $T < 10$ K — non-thermally desorbed from ice.

Note P Cygni profile - gas is infalling and this is the very dense gas!

Layer of water gas where ice is photodesorbed

H$_2$O gas ring

Ice formation

Photodesorption

n=2.10$^4$ – 5.10$^6$ cm$^{-3}$, T=10 K

Caselli et al. 2012
Schmalzl et al. 2014
Molecular Cloud

Pre-stellar Core

Embedded Protostar

Time

Star with Protoplanetary Disk

Warm (T > 100 K) inner "envelope" - hot core

LOW MASS PROTOSTAR

Cold (T ~ 10-20 K) outer "envelope" Forming disk (small size)

Outflow shock heated gas (T > 400 K)

Ice evaporation water vapor rich

Freeze-out water vapor poor

Hard to detect, critical stage

Water vapor rich
WATER IN LOW-MASS PROTOSTARS

Spectrally resolved line profiles with HIFI

N1333
L~20 \(L_{\odot}\)
D~750 lyr

Spitzer image

p-H\(_2\)O
ground-state
Line: 1 THz

\(\text{H}_2\text{O} \ 1_{11-0_{00}}\)
IRAS-4B
IRAS-4A
IRAS-2A

Absorption in outer envelope

outflow

Broad: outflow dominates, even for H\(_2\)\(^{18}\)O

Kristensen, Visser et al.
2010, 2012
Water is present in hot core (spatially unresolved emission)

Abundance consistent with ice evaporation?

This water may not be part of the planet formation story.

Coutens+ 2012
• Water is detected on small scales (< 100 AU)
• Water vapor abundance is <10^{-4} -- water is mostly as ice
PLANET FORMATION AND WATER
NEW PARADIGM OF PLANET FORMATION

- dust grows and settles to a dust rich midplane
- grains collide and grow to pebble size
  - barriers [bouncing/fragmentation (cm-size) and drift (m-size)]
- Pebbles form by coagulation and ice condensation
- Pebbles concentrate into dense clumps that contract to form planetesimals (current focus on streaming instability)

slide from A. Johansen
NEW PARADIGM OF PLANET FORMATION

- icy pebble size > silicate pebble due to higher fragmentation velocity
- After forming planetesimals growth is driven by pebble accretion
  (Johansen & Lacerda, 2010; Ormel & Klahr, 2010; Lambrechts & Johansen, 2012)
- Water ice line is isolated as a critical location

Water ice line pebbles ~cm sizes
terrestrial embryo
giant planet core
< water ice line pebbles ~mm sizes

top figure: Banzatti+ 2015
bottom fig: Morbidelli+ 2015
BULK COMPOSITION

• Focus on understanding bulk composition to look for signatures of giant planet origin.
  ➡ C/O ratio and C/H, O/H (N difficult to retrieve)

• At BASE level relate to formation:
  ➡ Assume core-accretion
    □ Core forms from solids
    □ Envelope forms from gas - reflects gas composition
COMPOSITION: C/O CARRIERS

Refractory

(C) PAHs and/or aliphatic hydrocarbons

(O) Silicates

Volatile

(C) CO, CO₂, organics

(O) H₂O, CO, CO₂
DISK BULK COMPOSITION & GAS GIANTS

- Clear focus on connective tissue has been the C/O ratio and icelines (Öberg, Murray-Clay, & Bergin 2011).

- Core/accretion formation
- Core is made of solids (refractory + volatile ices)
- Envelope is gaseous
WATER WORLD?
THE WATER SPECTRUM

JWST

[Diagram showing the water spectrum with JWST and various wavelengths and features such as H$_2$O bending vibration, H$_2$O rotational spectrum, CO fundamental, Silicate, o-H$_2$O ground-state, and Cometary volatile reservoir.]
WATER SNOWLINE

Hot water inside snowline (JWST)
Warm water near snowline (Far-IR)
Cold water snowline and beyond (Far-IR)

ground state line @ 179 µm

water spectrum: Blevins+ 16

Illustration by Jack Cook, WHOI Graphic Services)
Disk Bulk Composition: O/H

Debes et al. 2013

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

hot water

Zhang et al. 2013

Hogerheijde et al. 2011
cold water

Spitzer + Herschel - only 5 disks (Zhang+13; Blevins +16).
Water Abundance in TW Hya

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

3. Photodesorption layer - UV radiation must be present
Water Abundance
undepleted O

Du, Bergin, & Hogerheijde 2015
Water beyond the snow line.

\[ \text{[O II] } 63 \mu \text{m} \quad E_u = 228 \text{ K} \]

\[ \text{H}_2\text{O} 538 \mu \text{m} \quad E_u = 61 \text{ K} \]

\[ \text{H}_2\text{O} 269 \mu \text{m} \quad E_u = 53 \text{ K} \]

\[ \text{H}_2\text{O} 179 \mu \text{m} \quad E_u = 114 \text{ K} \]

Du, Bergin, & Hogerheijde 2015
Water Abundance depleted O

- Need to remove water ice from layers with UV (i.e. reduce photodes. efficiency)

Du, Bergin, & Hogerheijde 2015
Water beyond the snow line..

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Du, Bergin, & Hogerheijde 2015

\[ \text{[O I] } 63 \text{ } \mu\text{m } E_u = 228 \text{ K} \]

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Du, Bergin, & Hogerheijde 2015
THE EXISTING LANDSCAPE: ALMA

mm-sized grains are highly settled to disk midplane (Pinte+ 2016; Louvet+ 2018)

ALMA beam: 0.26” x 0.18”
(36 au x 25 au)

Louvet et al. 2018
No grain evolution

Krijt, Ciesla, & Bergin 2016
Grain Evolution

Krijt, Ciesla, & Bergin 2016
TW Hya is not alone...

- 13 systems surveyed by Herschel in the 2 ground state lines + some excited lines (Du et al. 2017)
- Result is systemic - water vapor is not present in gas.
- Water ice on small grains is not available in UV active layers.
• Earth water (partially) formed at low temperature ($T < 50$ K).

• Is diversity in comet population real? what does it mean?

• Herschel opened up this field - showed us the Kuiper Belt - this was critical.
The FUTURE

- Water content (Earth oceans)
  - Pre-stellar cores
  - Protostars
  - Disks (inner)
  - Disks (outer)
  - Disk ice mass
  - Debris disks
  - Comets

- Water D/H (Relative to Earth oceans)
  - Origins
  - SPICA
  - Herschel
  - JWST

Expected range
CONCLUSIONS

• For water vapor - there is no other than Herschel.

• Even ALMA with its amazing sensitivity will not equal Herschel’s contributions.

• Its legacy will last -> until the next facility with greater sensitivity launches.