THE HERSCHEL VIEW ON WATER IN STAR AND PLANET FORMATION

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- 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)











ICES ARE ABUNDANT AND COMMON!



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

WATER IN PRE-STELLAR CORES

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!



Caselli et al. 2012, ApJ, 759, 212, Hollenbach+ 2009, Klotz+ 2008, Bergin+ 2002

WATER DISTRIBUTION IN DENSE CLOUDS



LOW MASS PROTOSTAR



WATER IN LOW-MASS PROTOSTARS



N1333 L~20 L_{Sun} D~750 lyr Spitzer image

p-H₂O ground-state IRAS-4B Line: 1 THz RAS-4A outflow IRAS-2A and topy mar have a start and a start and a start W. mulikaner May Carl Absorption in outer envelope

 $H_2O 1_{11} - 0_{00}$

 $100 -50 \qquad 0 \qquad 50$ Velocity (km s⁻¹) Broad: outflow dominates, even for H₂¹⁸O 100 Kristensen, Visser et al. 2010, 2012

PROTOSTARS

Hot Core ≥100 AU Scale

- 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.



Visser et al. 2013, ApJ, 769, 19 Coutens+ 2012

PROTOSTARS

- Water is detected on small scales (< 100 AU)
- Water vapor abundance is <10⁻⁴ -- water is mostly as ice



Persson et al. 2013, A&A, 549, L3 Persson+ 2012, A&A, 541, A31 Taquet+ 2013, A&A, 768, L29

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



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
 - **D** Core forms from solids
 - Envelope forms from gas reflects gas composition

COMPOSITION: C/O CARRIERS

Refractory



(C) PAHs and/or aliphatic hydrocarbons

(O) Silicates

Volatiles





NASA / JHUAPL / SwRI / ROMAN TRACHENRO

(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?

102

2

-1

THE WATER SPECTRUM



WATER SNOWLINE



Disk Bulk Composition: O/H



Spitzer + Herschel - only 5 disks (Zhang+13; Blevins +16).

Water Abundance in TW Hya



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

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

 Photodesorption layer -UV radiation must be present

Water Abundance undepleted O





Water Abundance depleted O



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



THE EXISTING LANDSCAPE: ALMA

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



small micron sized dust

O - ALMA beam: 0.26" x 0.18" (36 au x 25 au) Louvet et al. 20<u>18</u>

No grain evolution



Krijt, Ciesla, & Bergin 2016

w 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.

TRANSFORMING PLANET FORMATION



• 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)

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.