The distribution of H$_2$O and CO in DR21

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The role of water in star formation

- Versatile molecule, more active than CO
  - in clouds (gas): cools down collapsing clouds
  - in disks (ice): glues grains together into planetesimals
  - on planets (liquid): brings molecules together, key to life

- Main reservoir of oxygen
- affects chemistry of many other species
- traces basic freeze-out and evaporation processes

- H₂O abundance varies strongly in SF regions
  - SWAS, ISO: 10⁻⁸ (cold) ... few 10⁻⁴ (warm)
  - Spatial distribution not well known
  - Spitzer / ground-based: only see warm gas

Herschel: the first high-resolution view of the bulk H₂O
WISH: water in star-forming regions with Herschel

- Key program in 429 hours of GT
  - goal: physical and chemical structure of SF regions

- Covers 90 sources
  - pre-stellar cores
  - protostars of low/high/intermediate mass
  - outflows
  - protoplanetary disks

- Uses HIFI and PACS spectroscopy
  - including small (2' x 2') maps

- Collaboration of >70 scientists
  - from >30 institutes world-wide
The low-mass protostar L1157 and its outflow

Spitzer IRAC

Herschel PACS

$\text{H}_2\text{O}$

$179 \, \mu\text{m}$

$L1157 \, \text{mm}$

$10^4 \, \text{AU}$

Strong line emission from the embedded protostar:

Herschel traces interaction more directly than Spitzer
High-mass star formation in WISH

- Subprogram with 127 hours of GT + 20 hours of MS time
  - goal: evolutionary connection between types of sources

- Observe 20 sources
  - infrared-dark cloud cores
  - protostars of low/high mid-IR brightness
  - hot molecular cores
  - ultracompact HII regions

- Uses HIFI and PACS spectroscopy of 20 H$_2$O lines
  - including small (2' x 2') maps

- Collaboration of scientists in Groningen, Bordeaux and Bonn
  - with associates world-wide
The DR21 region

- $L = 45,000 \ L_0$
- $d = 1.7 \ kpc$
- $M = 800 \ M_\odot$
- size $\sim 0.3 \ pc$
- Strong outflow
- Compact HII region

Observed with HIFI in June 2009 as part of PV program
HIFI data: dust, $^{13}$CO 10-9, $\text{H}_2\text{O}$ 1$_{11}$-0$_{00}$ @ 1100 GHz

- $^{13}$CO pure emission; $\text{H}_2\text{O}$ emission-absorption profile
- Both dust and lines extended over $\sim$1'
Central line profiles

- **Dense core**: $^{13}$CO narrow emission; H$_2$O absorption at $V = -3$ km/s
- **Outflow**: broad emission in both lines
- **Foreground cloud**: H$_2$O absorption at $V = +7$ km/s
  - known from ground-based low-$J$ CO spectra
Spatial distribution

- Dust extended over 35" FWHM
- Lines compact: 25" or less
- Foreground absorption broader (~30") and shifted ~10" N
  - Consistent with ground-based dust and CO maps
Radiative transfer model

- **Model dense core with RATRAN**
  - $T = 23 \ldots 117$ K
  - $n = 2\times10^5 \ldots 3\times10^7$ cm$^{-3}$
  - Find $^{13}$CO/H$_2 = 8\times10^{-7}$ and p-H$_2$O/H$_2 = 2\times10^{-10}$

- **Outflow & foreground: use RADEX**
  - foreground: $T=10$ K, $n=1\times10^4$ cm$^{-3}$
  - Find $N(^{13}$CO) = $7\times10^{15}$ cm$^{-2}$, $N$(p-H$_2$O) = $4\times10^{12}$ cm$^{-2}$
  - outflow: $T=200$ K, $n=3\times10^4$ cm$^{-3}$
  - Find $N(^{13}$CO) = $5\times10^{16}$ cm$^{-2}$, $N$(p-H$_2$O) = $1\times10^{16}$ cm$^{-2}$
Formation and destruction of H$_2$O

- Strong variations in ratio p-H$_2$O:$^{13}$CO
  - 1:5000 in dense core, 1:2000 in foreground, 1:5 in outflow

- Similar values for dense core and foreground: *coincidence*
  - Core: high density $\rightarrow$ strong freeze-out on dust grains
  - Foreground: low extinction $\rightarrow$ rapid photodissociation

- Enhanced H$_2$O in outflow: *real*
  - high temperature
    $\rightarrow$ grain mantle evaporation
So what's next?

- Multi-line studies → abundance *profiles*, not radial averages

- Multi-source studies → trace $\text{H}_2\text{O}$ *evolution* during MSF
  - massive pre-stellar cores
  - high-mass protostellar objects
  - hot molecular cores
  - ultracompact HII regions

- Related molecules (OH, $\text{H}_3\text{O}^+$, $\text{H}_2\text{O}^+$ ...)
  - understand chemical impact of $\text{H}_2\text{O}$
Comparing H$_2$O with CO & dust

- H$_2$O seen in emission and absorption
- Double horn profile: central dense core
- Gaussian emission: surrounding cloud
- Significant continuum detected
- $^{13}$CO 10-9 only shows emission
- Emission extended in NS direction:
  - H$_2$O over 50", $^{13}$CO and dust 90"
The Herschel view of star-forming regions
Implications

- Water seen wherever energy injected into gas
  - elucidates key episodes of stellar birth: energy exchange
    - gravitational collapse
    - outflow ejection
    - stellar heating of disks and envelopes

- Water seen in both emission and absorption
  - line profiles essential to understand maps
  - must exploit synergy between HIFI and PACS

- Water line profiles
  - are complex and highly informative
  - trace hidden gas components
  - CO only shows emission
High-mass stars

- 1% by number, 99% by impact
  - major energy source for ISM
  - shape the Galactic environment
  - link to starbursts and early Universe

- Formation not well understood ...
  - low-mass stars: monolithic (disk) accretion
  - scale-up: requires high temperature / turbulence
  - alternatives: coagulation / competitive accretion

- ... due to instrumental limitations
  - large distance: need angular resolution
  - large extinction: need far-IR and submm range

Herschel and ALMA will revolutionize this field!
Phases of high-mass star formation

THE FORMATION OF STELLAR CLUSTERS

Pre-stellar phase
Complex of infrared dark clouds
Warm molecular phase
Submm spectrum of warm gas
Compact ionized phase
Radio image of plasma pockets
Cloud disruption phase
Mid-Infrared image of hot dust
Low-mass protostar HH46: high-velocity [OI]

- Also CO and H$_2$O lines detected
The intermediate-mass protostar NGC 7029

- Strong H$_2$O, CO, OH and O lines detected
- Contributions from envelope and outflow
- Need HIFI to disentangle these!
The high-mass protostar AFGL 2591

- absorption at $V = 0$ km/s: foreground cloud
- absorption at $V = -8$ km/s: intrinsic
- narrow emission at $V(\text{LSR})$: outer ring of cool water
- broad emission at $V(\text{LSR})$: molecular outflow
- SWAS saw pure emission: continuum is compact

$\text{O-H}_2\text{O} \ 1_{10}-1_{01} \ 557$ GHz