Exploring the Physical and Chemical Diversity of the Solar System: The Submillimeter Approach

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Studying a closeby evolved system: what's the point?

Information relevant to exoplanetary systems and disks:

- clues to **system formation**: isotopic ratios, bulk densities, dynamical families, ...

- characterization of **chemical and physical processes**: seasonal cycles, gas escape, surface alteration, volcanism, ...

- retracing the **history of individual bodies**: climate, water content, organic chemistry
What is (sub)mm radiation in the solar system?

Thermal emission (30-700K)
What is (sub)mm radiation in the solar system?

Thermal emission (30-700K)

- Eris
- Herschel
- Spitzer
- SMA
- IRAM
- ALMA
- JVLA

Frequency (GHz)
What is (sub)mm radiation in the solar system?

- Surface continuum emission (airless bodies/ transparent atmosphere)

  *Pluto/Charon system, SMA, Gurwell et al., 2005*

- Atmospheric pseudo-continuum collisional emission (pressures ~1 bar)

  *HC$_3$N line on Titan, IRAM-, Moreno et al., 2005*

- Atmospheric rotational lines (pressures 1bar -> 1microbar)
Perfomed observation projects

- Mapping CO, Detection SO₂, H₂O, HDO, SO
  - Mesospheric dynamics

- Mapping CO
  - Detection H₂O₂, H₂O, HDO
  - Winds

- PH₃, H₂O, NH₃, CO, CS detections
  - HCN mapping

- Io : mapping SO₂, SO
  - Detection NaCl, KCl
  - Winds

- Detection H₂O

- Detection CO, HCN, H₂O

- Detection of Pluto and 7 other Kuiper Belt Objects, CO detection

- Brightness temperature measurements

- Titan : Detection HCN, CO, HC₃N, CH₃CN, H₂O
  - Winds
I) Atmospheric composition

Detection of rotational lines of atmospheric compounds: CO, HCN, HDO, H₂O, SO₂, SO, ...

- Line profile analysis: **column density- vertical mixing profile**

**LTE emission**  
Collisional and Doppler broadened profiles  
Differential sounding

CO(3-2) line on Neptune, JCMT, Hesman et al., 2007
I) Atmospheric composition

- Line emission mapping: horizontal distribution

Single dish instruments: Venus, Jupiter
Interferometers: ice giants, Mars, large moons and asteroids, Pluto (ALMA)

CO(3-2) and H(4-3) integrated line emission on Neptune, SMA, Moullet et al., 2011
Io, Jupiter's volcanic moon

- Strongest **volcanic activity** in solar system
- \( \text{SO}_2 \) **frost**-covered surface
- Environment: neutral clouds and **plasma torus**
- \( \text{SO}_2 \) **atmosphere**. tenuous (1-10nbar)

*Schneider and Bagenal, 2007*
Io's atmosphere processes

- Thermal escape
- Torus stripping (~1 ton/s)
- Photochemistry
- Frost sublimation
- Volcanic outgassing
- Gas condensation
- Surface sputtering

- What are the expelled volcanic gases?
- How is the atmosphere replenished?
- How (much) does the atmosphere feed the environment?
Atmospheric structure interpretations from disk-integrated observations:

- very **localized** (<20%)
  - hot (~500 K)
  - quite dense (~6e^{17} cm^{-2})

- **spread-out**
  - cold (~140 K)
  - lower density (~1e^{16} cm^{-2})

**SO$_2$ lines analysis**

**SO$_2$ lines, IRAM-30m, Lellouch et al., 1990**
SO$_2$ mapping

- SO$_2$ spatially extended, local-hour restricted: Coherent with sublimation-sustainment

- Comparison to plume emission models: volcanic contribution is minor
Plume composition depends on vent temperature, conduit pressure, atomic ratios: defines volcanic regimes
Sulfur monoxide

- more spatially concentrated than SO$_2$
- volcanic emission can contribute to <30% of SO content
- coherent with SO$_2$-photolysis being the main SO source
• (Low quality) Mapping suggests localized emission

• **Volcanism can be the sole NaCl source** if NaCl/SO₂ 0.6-2.5 %

• Short atmospheric lifetime: **plume activity tracer on day-side**
Tentative detection of KCl line, APEX, Moullet et al., 2013

Expected source of K in neutral clouds, Jupiter's rings

- **Tentative detection:**
  \[ \text{KCl/SO}_2 = 5(\pm 2) \times 10^{-4} \]

- **Consistent with purely volcanic sustainement**

Very low Na/K ratio (~2.7):
Ultra-potassic lavas?
Vaporization fractionation?

*Tentative detection of KCl line, APEX, Moullet et al., 2013*
Next composition exploration: ALMA

Observing time awarded in Cycle 0 and Cycle 1

Goals: firm detection of KCl, detections of SiO, S$_2$O, $^{34}$S..: → constrain volcanism

Spatial resolution $\sim$0.3": → characterize sublimation
II) Atmospheric dynamics

Doppler-shift mapping in line cores directly indicate **projected wind velocity**

High altitudes **rarely probed** by other techniques

$^{13}$CO line cores in Venus, JCMT, Clancy et al., 2012

Coupling of temperature and wind-field to **constrain GCMs** (global circulation models)
II) Atmospheric dynamics

**Titan**
(450km altitude)

**Mars**
(50km altitude)

**Io**
(ground level)

\[\text{CH}_3\text{CN Doppler-shifts, IRAM-PdBI, Moreno et al., 2005}\]

\[\text{CO Doppler-shifts, IRAM-PdBI, Moreno et al., 2009}\]

\[\text{SO}_2\text{ Doppler-shifts, IRAM-PdBI, Moullot et al., 2008}\]
Venus' atmosphere dynamic structure

- Zonal retrograde wind
- Subsolar-antisolar wind (day-to-night)

Altitude

Temperature

Airglow mapping

Cloud monitoring (VMC-VeX)

Pioneer probes

![Diagram showing Venus' atmosphere structure with altitude and temperature axes, highlighting the mesosphere, troposphere, and thermosphere. The diagram includes Zonal retrograde wind and Subsolar-antisolar wind (day-to-night).]
Venus' atmosphere dynamic structure

Combination of day-night/zonal winds

High temporal/spatial variability

65 km

70 km

80 km

90 km

100 km

110 km

Airglows and IR emission monitoring $O_2$, NO, OH (VIRTIS-VeX)

Doppler-shifts CO (mm)

Doppler-shifts $CO_2$ (IR)

Doppler-shifts reflected sun-lines (Fraunhofer)
Venus' atmosphere dynamic structure

Coupling thermal field / wind field?

Cyclostrophic equilibrium break?

Airglows and IR emission monitoring $\text{O}_2$, NO, OH (VIRTIS-VeX)

Doppler-shifts CO (mm)

Doppler-shifts $\text{CO}_2$ (IR)

Doppler-shifts reflected sun-lines (Fraunhofer)
CO horizontal distribution

CO line cores sound:

90-105 km CO(1-0)
95-110 km CO(2-1)

CO(1-0) altitude line contributions, Moullet et al., 2012

CO(1-0) mapping, morning hemisphere, IRAM-PdBI, Moullet et al., 2012

CO lines are deeper on the night-side:

Displacement of CO from day to night-side
Venus' phases and wind geometry

Superior conjunction (day)

Quadrature East (evening)

Quadrature West (morning)

Inferior conjunction (night)
Interferometric Doppler-shift mapping

- Superior conjunction

Quadrature East

Quadrature West

CO(1-0) and CO(2-1) mapping, SMA and CARMA. Errors 30-40 m/s

- Day to night wind dominating
- Significant velocity variations with local-hour
Observations IRAM-PdBI 2007/2009, morning hemisphere, precision 10-20m/s

- Temporally stable wind-field
- Global \textbf{day-to-night flow 200 m/s}
- \textbf{Equatorial retrograde zonal jet} \sim 100m/s
- Latitudinal / local hour wind variations

\textit{CO(1-0) Doppler-shifts, morning hemisphere, IRAM-PdBI, Moullet et al., 2012}
Wind structure more complex than a combination of day-to-night / zonal flow

To estimate altitude wind-shear:
→ simultaneous use of multiple lines

To detect wind variations at high latitudes:
→ high spatial resolution (~0.5-1'"

To detect quick temporal variations (~1 hour):
→ snapshot wind measurements

Further investigations

Oxygen airglow monitoring, VEx-VIRTIS, Hueso et al., 2008

ALMA
Thermal emission radiative effects:

Snell-Fresnel laws at surface/air interface:
- \( n > 1 \)
- \( n = 1 \)

Surfaces not transparent at thermal wavelengths:
- \( -> \text{refraction index, surface roughness} \)
- \( -> \text{absorption coefficient} \)

The total emission combines contributions from different depths, down to \( \sim 10 \lambda \)
Temperature field depends on geometric properties: shape, rotation rate

orbital properties: hel. Distance, pole direction

surface properties: albedo, thermal inertia

Temperature distribution model for Haumea, Mueller et al., 2008
Optical magnitude \( \propto \text{albedo} \cdot D^2 \)

Thermal emission \( \propto B(\nu, T((1-a)^{0.25})) \cdot D^2 \)

Independent estimate of albedo and equivalent size

If mass known (binaries): density estimate

\textit{Detection of Centaur 1999 TZ1, IRAM-30m, Moullet et al. 2008}
Thermals models defined through beaming parameter $\eta$

- Low inertia
- High inertia

$\eta = 1$

- Slow Rotator model

Varying $\eta$

$\eta = 2$

- Quick Rotator model

$\eta$ constrained by multi-wavelengths thermal photometry
Time-resolved radiometric method can distinguish **albedo distribution/ shape** (apparent size variation)

*Vesta's thermal lightcurve, SMA*

*Haumea's optical and thermal lightcurves with Herschel, Lellouch et al., 2010*
The case for Kuiper Belt Objects

- Analog of planetesimals in \textit{debris disk}

- Most pristine material in the Solar System

1000+ KBOs
200 Scattered objects

← Eris

30 K

70 K
50 K

Courtesy of Minor Planet Center
Role of thermal observations

- Measurement of size distribution: collisional grinding/accretion in a planetesimal belt

- Density (ice to rock ratio): physical properties in the primitive Solar nebula

- Albedo distribution, albedo/size correlations: physical and collisional processes on cold/distant surfaces

Densities and diameters, Brown et al., 2012
Role of thermal observations

~4 sizes with ISO

~45 sizes with Spitzer-MIPS (Centaurs)

~8 sizes with IRAM-30m MAMBO bolometer

The trans-neptunian object UB₃₁₃ is larger than Pluto

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- Herschel : 140 (40) detections PACS, 17 detections SPIRE

Sensitivity very limiting !
ALMA B6/B7 (full science): More efficient than Herschel

Diameter threshold for $5\sigma$ detection ($\sim 2$ h integration)
- at 30 AU: $110$ km
- at 50 AU: $210$ km

$\rightarrow$ size/albedo on 600+ objects

Filling size distribution, albedo/size database for correlations

*Diameter detection threshold as a function of Sun distance, Moullet et al., 2011*
ALMA: size and shapes

Direct analysis of visibilities (~ imaging) combined with lightcurve analysis

Possible on ~ 30 bodies larger than 0.015"

→ non model-dependant sizes

→ ellipticities or 3-D shape (even on pole on geometry)

Constraints on internal strength, density

Simulated Charon visibilities @345 GHz, Mouillet et al., 2011
First KBOs thermal mapping possible, resolution $\sim 15$mas

Detection of 10% temperature variations on 6 large bodies

→ horizontal variations of albedo/thermal inertia/temperature

Constraints on resurfacing processes

*Pluto, Band 7, very extended configuration simulation*
Large fraction of multiple systems: ~10%. Many ~equally-sized.

Separations 2'' → contact binaries.
ALMA resolution (B7) -> 0.01'' (Hubble: 0.04'')

→ individual size/albedo

→ system density

Constraints on system formation (capture, disruption)
What does (sub)mm radiation in the Solar System tell us?

- Atmospheric composition
- Atmospheric structure
- Wind and temperature fields
- Surface thermal and reflective properties
- Small bodies' equivalent sizes

Unique and essential measurements to constrain
- climates
- surface and atmospheric processes
- collisional /chemical evolution
(Sub)mm Solar System science in the ALMA era: a new range of possibilities

- **Sensitivity increase** (80-900 GHz): factor 10-40.
  - minor species detections, tenuous atmospheres, small/distant bodies
- **Spatial resolution**: factor 10-20
  - High-res mapping of planets, mapping of large asteroids and KBOs, limb resolution
- **Imaging snapshot capabilities**: quasi-instantaneous
temporal monitoring of winds and quick phenomena
Performed/accepted projects

- Sulfur and HDO mapping, Chlorine species, winds
- Storm CO and temp. mapping
- Titan: nitrile detection and mapping, winds
- Medium-sized KBOs detection
- Io: chemistry, winds
- HCN, CO and isotopologues
- Comet PanStarrs