Solar system science using millimeter wavelength with NOEMA

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Content of this talk

• Introduction of the science back grounds of the observational study of Solar system objects.
  ➔ This talk will more focus on the “planetary atmosphere” science.

• Expectations for NOEMA observations:
  
  3-D Temperature and wind mapping of the terrestrial planets (Venus, Mars).
  Line survey of Titan (or other outer planets) atmosphere.
What are the science drivers of Solar system observations?

Perhaps a bit biased by my own opinion...but just let me say with no fear of misunderstanding...

**Characterize physical & chemical processes in the Solar system: as individual objects, and also as a “system” consisting of several objects.**

- Individual object is often further divided into sub-systems such as solid body, atmosphere (ocean), and the surrounding plasma environment (magnetosphere).
- Several physical/chemical processes occur in each of the sub-system.
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**Characterize physical & chemical processes in the Solar system: as individual objects, and also as a “system” consisting of several objects.**

- Availability of space-missions, including the in-situ measurements, enables us to achieve the “detailed characterization” of our Solar system: e.g., understanding the different/ubiquitous phenomena in Venus, Mars, and Earth.
“Sizes” of Solar system objects

From the spatial resolution point of view, NOEMA perfectly fits with “planets & their moons” observations, while ALMA can be used to “minor body & distant object” observations.

<table>
<thead>
<tr>
<th>Diameter [arcsec]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>10 – 60</td>
</tr>
<tr>
<td>Jupiter</td>
<td>30 – 50</td>
</tr>
<tr>
<td>Mars</td>
<td>5 – 25</td>
</tr>
<tr>
<td>Uranus</td>
<td>3</td>
</tr>
<tr>
<td>Neptune</td>
<td>2</td>
</tr>
<tr>
<td>Jovian moons</td>
<td>&lt; ~1.5</td>
</tr>
<tr>
<td>Titan</td>
<td>0.8</td>
</tr>
<tr>
<td>Juno (asteroid)</td>
<td>~0.2</td>
</tr>
<tr>
<td>Pluto, KBOs, etc.</td>
<td>&lt; ~0.1</td>
</tr>
</tbody>
</table>
Several topics of the Solar system planet

- **Terrestrial Planets**
  - Supply, escape of volatiles
    - Volcanic activity, Jeans escape.
  - Life (astrobiology)
    - “Habitable Zone”. Search for liquid water, organic molecules.
  - Atmosphere
    - Understanding composition, clouds, haze, dust aerosols.
  - Energy budget
    - Radiative equilibrium between Solar incoming flux. Albedo feed-back.
  - Meteorology, Climate
    - Spatial and temporal variations on Temperature, Wind (dynamics), Chemistry, Cloud microphysics.

- **Solid/Inner planet**
  - Composition, Evolution, Tectonics, Seismology, etc.

- **Gas Giants**

- **Moons**
  - Origins, Interaction with planets.
Several topics of the Solar system planet

- **Terrestrial Planets**
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- **Gas Giants**
  - Planetary formation
  - Based on C/O ratio, isotopes.

- **Solid/Inner planet**
  - Composition, Evolution, Tectonics, Seismology, etc.

- **Atmosphere**
  - Radiative equilibrium between Solar incoming flux. Albedo feed-back.
  - Understanding composition, cloud, haze, dust aerosols.

- **Energy budget**
  - Spatial and temporal variations on Temperature, Wind (dynamics), Chemistry, Cloud microphysics.

- **Moons**
  - Origins, Interaction with planets.
  - New “habitable zone” in inner oceans of Icy Moons.

- **Meteorology, Climate**
  - Spatial and temporal variations on Temperature, Wind (dynamics), Chemistry, Cloud microphysics.
Advantages of mm-wave observations of planets/moons

1. Millimeter & sub-mm wave → Lines of many key molecules in the planetary atmosphere

2. Heterodyne spectroscopy → Spectrally-resolved molecular lines allow ...

- Studying atmospheric composition, atmospheric chemistry.
  Search for new species (photochemical species, organic molecules, etc.). Minor species in the atmosphere sometimes play a significant role in the planetary system like stratospheric O3 in the Earth.

- Sounding atmospheric temperature (energy balance within the planet).
  Temperature profile is the most fundamental parameter in the planetary atmosphere.

- Sounding atmospheric dynamics (wind).
  Wind induced Doppler-shift of the molecular lines are observable!
Molecular lines of planet atmosphere

Neptune CO(3-2) [Hesman et al. 2007]

Contribution functions indicate the altitude range which the emission probes at specific frequencies.

Pressure = Vertical altitude in the atmosphere

Line shape (line width) → “Pressure-broadened”. CO in the different pressure levels (i.e. different altitudes) induces different broadening.

→ **Vertical profiles** of Temperature and CO can be constrained.

Contribution functions indicate the altitude range which the emission probes at specific frequencies.
3-D mapping of atmospheric temperature

Thermal structure of Venus middle/upper atmosphere [Piccialli et al., 2017]

At 100 km, temperature decreases from the morning to evening terminator (i.e. diurnal variation); while such a trend is inverted at 74 km.

Fig. 13. Global maps of retrieved ALMA temperatures at the pressure levels of: 11 mbar (~74 km) and 0.01 mbar (~100 km). The four days of observation are displayed.
Atmospheric wind

Doppler-wind map at ~100 km altitude of Venus atmosphere [Sagawa et al., 2007]

Venus atmosphere is known to rapidly rotates in the westward direction as the global wind regime (a.k.a “super-rotation”), and the line-of-sight projected wind pattern should appear like this.

...however, the measurement indicated that there should exist a different wind regime in the upper atmosphere (at least, at 100 km altitude).
Atmospheric wind

Doppler-wind map at ~100 km altitude of Venus atmosphere [Sagawa et al., 2007]

Blue: Line-of-sight wind moving towards observer.
Red: Line-of-sight wind moving away from observer.

If we introduce vertical transportation of the angular momentum due to “waves” phenomena in the upper atmosphere...

Analysis of CO(2-1) data obtained by SMA

New model
3-D mapping of atmospheric temperature & winds

• Atmospheric temperature (above the deep troposphere) is controlled by
  - not only by radiation (absorption of Solar flux and atmospheric infrared emissions)
  - but also by dynamics (advection) and wave propagations.
• And, dynamics is controlled by the thermal structure.

• Currently several key parameters for the wave propagation in the Venus atmospheric
circulation model are ad-hocly “tuned”.
• Constraining the 3-D thermal structure of T and Wind from the observations provides key
information to understand what kind of meteorological phenomena are occurring there.
Expectations for NOEMA observations

- Increase of the observational data at different epochs (monitoring)

**Planetary atmosphere has strong temporal variations!!**

- Seasonal or local-time dependent (diurnal) variabilities.

Venus: Presence of a very wide-spread thermal fluctuation, fixed to the topography (i.e. stationary) at 70 km level [Fukuhara et al., 2017]. This feature has been observed only at the evening local times.

Long temporal variation of SO\textsubscript{2} abundance in the Venus atmosphere.
Expectations for NOEMA observations

• Increase of the observational data at different epochs (monitoring)

Planetary atmosphere has strong temporal variations!!

* Sporadic event.

Jupiter: **SL9 impact**. A large amount of volatiles such as CO, HCN, CS and water vapor are injected into Jovian upper atmosphere.

Stratospheric H2O is still biased in the southern hemisphere [Herschel, Cavalie et al. 2013].
Expectations for NOEMA observations

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Planetary atmosphere has strong **temporal variations!!**

* Sporadic event.

Another example: CS. After 20 yrs, the abundance of CS reduced to 10% of the injected level [Iino et al., 2016].
Expectations for NOEMA observations

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Planetary atmosphere has strong **temporal variations**!!

* Sporadic event.

Mars: Sometimes the planet is entirely covered by very thick dust opacity ("**global dust storm**"). It is considered that the atmospheric structure inside such a storm is completely changed from the normal condition.
Expectations for NOEMA observations

• Increase of the observational data at different epochs (monitoring)

Planetary atmosphere has strong **temporal variations**!!

* Sporadic event.

Actually, a very strong global dust storm event (for the first time in 10 yrs!) is on-going!
Millimeter-wave can probe inside the dust storm since the dust particles are < micron sizes.
Advantages of mm-wave observations of planets/moons

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  Search for new species (photochemical species, organic molecules, etc.). Minor species in the atmosphere sometimes play a significant role in the planetary system like stratospheric O3 in the Earth.

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Titan atmosphere: a laboratory of organic species

• The best target to test whether “the life has been generated in the atmosphere”.

*Credit: Iino*
Line survey in mm-wavelength

Past observations of nitriles in the Titan atmosphere [IRAM30m, Marten et al. 2002]

Single-dish observations: Limited by the dilution of the Titan emission due to large beam size.
Line survey in mm-wavelength

Spectra from the ALMA data taken for the calibration purpose [Cordiner et al. 2015]

Figure 1. ALMA spectra observed 2012 July 3–4, integrated over a circular region of radius 1' centered on Titan. Titan’s continuum emission has been subtracted. Prominent emission lines are assigned by species; bold typeface highlights the C$_3$H$_2$CN emission features. The small absorption feature at 237.146 GHz is attributed to ozone in the Earth’s atmosphere.
Line survey in mm-wavelength

Isotopologues of HCN [Molter et al. 2016]
Isotopic fractionation = a key to constrain the chemical pathway.
Line survey in mm-wavelength

Survey of all the ALMA Titan data (incl. calibration data) [Iino et al.] (> 40 TB, >2200 spw!!)
Line survey in mm-wavelength

Survey of all the ALMA Titan data (incl. calibration data) [Iino et al.] (> 40 TB, >2200 spw!!)
Expectations for NOEMA observations

• “Dedicated” line survey, and detecting seasonal variation of their abundances.

Do not need to spatially resolve Titan disk (0.8”), but need the multi-epoch observations in order to trace any seasonal evolutions of poleward biased-distribution. Titan seasonal cycle = 30 year period. Currently the Northern hemisphere is more observed from the Earth.

Moment-0 map of HC3N [work by lino]
Summary

• NOEMA’s spatial resolution is a preferable scale for doing many Solar system planetary sciences.

• Observation of “temporal variation” (i.e. monitoring observation) is the key: --- this is what may be unfit for ALMA.

• Possible science cases for NOEMA are...
  3-D Temperature and wind mapping of the terrestrial planets (Venus, Mars)
  Line survey of Titan (or other outer planets) atmosphere