Exploring Our Solar System: Planets, Moons, and Small Rocky Bodies

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Timescale < 10 My
* NOT TO SCALE

http://mrsbrownart.com/
Variety of:

density
size
bulk composition
atmospheres
The Periodic Table of ExoPlanets

1,070 Confirmed Exoplanets

Mercurians: $10^{-5} - 0.1 \, M_E$
Subterrans: $0.1 - 0.5 \, M_E$
Terrestrial: $0.5 - 2 \, M_E$
Superterrans: $2 - 10 \, M_E$
Neptunians: $10 - 50 \, M_E$
Gas Giants: $> 50 \, M_E$

Hot Zone:
- Hot Mercurians: 1 (0.1%)
- Hot Subterrans: 6 (0.6%)
- Hot Terrans: 16 (1.5%)
- Hot Superterrans: 100 (9.3%)
- Hot Neptunians: 153 (14.3%)
- Hot Jovians: 462 (43.2%)

Warm ‘Habitable’ Zone:
- Warm Mercurians: 0 (0%)
- Warm Subterrans: 0 (0%)
- Warm Terrans: 0 (0%)
- Warm Superterrans: 10 (0.9%)
- Warm Neptunians: 5 (0.5%)
- Warm Jovians: 106 (9.9%)

Cold Zone:
- Cold Mercurians: 0 (0%)
- Cold Subterrans: 0 (0%)
- Cold Terrans: 0 (0%)
- Cold Superterrans: 4 (0.4%)
- Cold Neptunians: 10 (0.9%)
- Cold Jovians: 184 (17.2%)

Stellar Systems:
- 635
- 126
- 29
- 10
- 5
- 4
- 1

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(PHL @ UPR Arecibo)
Solar system studies inform on:

- **Protoplanetary physical and chemical conditions:** Comets, Kuiper Belt Objects and chondrites, isotopic ratios, bulk densities

- **Dynamics of late planetary system formation:** migration, mixing

- **Planetary processes:** seasonal cycles, gas escape, surface alteration, volcanism, ...

- **Evolution of individual bodies:** climate, water content, organic chemistry
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Solar System submm/cm radiation

- Thermal emission (30-700K)
  - surfaces (continuum)
  - atmospheres (rotational lines)

Mercury

(sub) millimeter

Herschel

IRA

SMA

ALMA

JVL/GBT

Spitzer
Solar System submm/cm radiation

Thermal emission (30-700K)
- surfaces (continuum)
- atmospheres (rotational lines)
Solar System submm/cm radiation

Frequency (GHz)

- ALMA
- Herschel
- Spitzer
- JVLA/GBT
- IRAM
- SMA

Eris

Thermal emission (30-700K)

- Synchrotron Emission

- centimeter

Solar System submm/cm radiation
A wealth of ground-breaking results ...

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

Brightness temperature measurements

Mapping CO Detection H₂O₂, H₂O, HDO Winds

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

Io : mapping SO₂, SO
Detection NaCl, KCl Winds

Detection of 8 Kuiper Belt Objects

Detection H₂O

Detection CO, HCN, H₂O

Detection PH₃, CO, H₂O

Titan : Detection HCN, CO, HC₃N, CH₃CN, H₂O Winds

Comets volatile composition
... and of new possibilities opened by ALMA and EVLA

- **Sensitivity increase**: factor 3-40
  - minor species detections, tenuous atmospheres, small and distant bodies

- **Spatial resolution**: factor 10-20 (ALMA)
  - High-resolution mapping of planets, thermal mapping of large asteroids and KBOs
ALMA projects (Cycle 0/ Cycle 1)

- Sulfur and HDO mapping, Chlorine species, winds
- Io: chemistry, winds
- Storm CO and temp. mapping
- Titan: nitrile detection and mapping, winds
- Comets Lemon, ISON
- HCN, CO and isotopologues
- Medium-sized KBOs detection
**Venus:**
Mapping HDO

**Io:**
Mapping SO$_2$ and volcanic species

**Neptune:**
mapping disequilibrium species

**Kuiper Belt Objects**
Size and surface properties
The Kuiper Belt: A debris disk analog in our system

- >1500 'planetesimals' (30-3000 km)
- Ice/rock surfaces
- Most pristine material in the Solar System
- **Size distribution:**
  
  *collisional grinding and accretion* processes in a planetesimal belt

- **Density** *(ice to rock ratio):*
  
  composition of the protoplanetary disk

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*Densities and diameters in the Kuiper Belt, Brown 2013*
Multiple system imaging

Independent size /reflectance (albedo) constrain **multiple system formation:**

- planetesimals capture
- collision rate

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

Simulation Haumea system, ALMA Band 7
Independent size /reflectance (albedo) constrain **multiple system formation**:

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- collision rate

**ALMA resolution power will be higher than Hubble's**

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*Simulation* Haumea system, ALMA Band 7

*Pluto/Charon system, SMA, Gurwell et al., 2005*
Atmospheric composition: Internal end external sources

Water tracers (HDO, $\text{H}_2^{18}\text{O}$) and disequilibrium species: indications of past and active sources

D/H ratio:
- retracing water origin/
- chemical mixing

Persson et al., 2013
Venus: water above clouds

Ultimate source of water: volcanic or cometary

Water vapor product of cloud evaporation:

\[ \text{H}_2\text{O} + \text{SO}_3 \leftrightarrow \text{H}_2\text{SO}_4 \]

Large temporal and spatial variations detected with ALMA
Neptune stratosphere

CO and HCN lines indicate abundance increase w altitude:
→ (partial) external origin

Mapping supports:
- continuous (non-equatorial) or ancient supply
- specific HCN destruction mechanism

Stratospheric lines mapping, SMA
Mouillet et al., 2012
Characterizing unique worlds: Io, the volcanic moon

Strongest **volcanic activity** in solar system

SO$_2$ frost-covered surface

SO$_2$ atmosphere, tenuous (1-10 nbar)

Geissler et al., 2007: Plume distribution
A sublimation-sustained $\text{SO}_2$ bulk atmosphere

Atmosphere beyond volcanic regions
Distribution consistent with frost maps

**Steep latitudinal cutoff**

$\text{SO}_2$ integrated emission,
IRAM-PdBI, Moullet et al., 2008

$\text{SO}_2$ integrated emission,
ALMA, Moullet 2013
Identifying the volcanic contribution

Volcanic species (KCl, SO) trace **location of active volcanoes**

Different locations suggest different plume compositions

*Atmospheric emission, ALMA, Moullet et al., 2013*
Characterizing the properties of solar system bodies to:

- retrace solar system history
- identify chemical and physical processes
- understand disks evolution

The contribution of ALMA and EVLA is unique and essential!