Exploration and Investigation of Solar System Formation

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Outstanding Questions

• What were the initial stages, conditions, and processes of solar system formation?

• How did the giant plane accrete?

• What governed the accretion, supply of volatiles, and evolution of atmospheres.

• What role did migration and bombardment play?
How should we explore?

- Review recent results across the solar system
- Recognize new approaches are required.
- Adapt as new discoveries are made.
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<tr>
<th>Pressure (bar)</th>
<th>Details</th>
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<tr>
<td>1 bar</td>
<td>Jupiter: Giant planet atmospheres are complicated probes carry risk to mis-interpretation.</td>
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<td>10 bar</td>
<td>Internal structure models can help with composition constraints (core is diffuse, low heavy elements, layered? Impact created?)</td>
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<td>Magnetic fields are integrally linked to deep interior structure and atmospheric dynamics.</td>
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<td>Satellites are worlds onto themselves.</td>
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Saturn

• Enceladus plumes.
• Titan liquid methane rain.
• Saturn rings as a seismometer.
• The symmetry of Saturn magnetic field
• Gravity results suggest Saturn very different than Jupiter.
Mercury

- Large Core, implies light elements
- Craters vs impactor flux models imply large volcanic deposits 3.5 Ga (Byrnes et al 2016).
- Field 100 weaker than Earth’s. Inductive response sounds core-mantle boundary.
- Volatile composition rich in Na, K, Cl, S and C in crust
- Polar regions high in H (water ice). Near equator, organic rich, implying cometary source
Venus

- Continent like features (Tessarae)
- Iron poor compared to basaltic plains
- Losing water via solar wind
- Plate tectonics?
- Japanese Akatsuki observed gravity waves at cloud tops
  - Coupling between atmosphere and surface topography: atmosphere and interior dynamics
Moon

- New Interpretation Re: Apollo Discoveries
  - Cratering leads to Heavy Bombardment
  - Composition/Isotopes
  - Age and Origin of Moon
  - Presence of water
  - Volatiles: depletion implies similar source mechanism as Earth
Asteroids

- Outgassing
- Dawn:
  - Vesta parent of HED meteorites
    - Iron core, early differentiation
    - Heavily cratered between planets and smaller asteroids
    - Surface contamination by carbonaceous material
  - Ceres: early global ocean
    - Partially differentiated
    - Water/ice on surface
    - Active volatile rich world
Comets

• Rosetta: D/H ratio 3x terrestrial water
  – Because this is only one comet: does not place major constraints on water delivery to Earth.
  – Range of D/H in comets? What does this mean?
  – Molecular oxygen observed at 67P C-G
    • Formation implications
    • Observed morphology constrains formation and evolution
Pluto and Kuiper Belt
Exoplanets
Water: In the Universe

Fundamental Importance beyond the search for life
Oxygen is the $3^{rd}$ most abundant element
Likely the most common multi-element molecule
Where did the water on Earth originate?
Comets sampled thus far don’t match
What was the history of water and volatiles in our early solar system?
How, when, and where did the planets form?
Galileo results show similar enrichment in key elements, independent of volatility.

Results imply Jupiter formed colder and/or further out than 5 AU.

Solid material that enriched Jupiter was most abundant solid material in early solar system.
But it gets more complicated...
D/H Across the Solar System

Clark et al. Icarus 321, 2019
H isotopic composition of water

Alexander, 2017 The origin of inner Solar System water, Phil. Trans. R. SocA.
The H isotopic of water as (with guess) of distance from Sun

Alexander, 2017 The origin of inner Solar System water, Phil. Trans. R. SocA.
Jupiter: Implications

Oxygen is the remaining key element abundance “unknown” from Galileo Probe

Discriminates among theories on how Jupiter heavy element enrichment occurred.

Constrains mass of Jupiter’s molecular envelope

Implications for giant planet formation: how, when and where?
So where are we now?

- Planetary interiors can constrain composition
- Giant planet atmospheres are not homogeneous, measurements of isotopes and noble gases are potentially still useful
- All small bodies appear to be outgassing volatiles
- Ocean worlds exist beyond habitable zone and are also outgassing volatiles

We must take this new knowledge and mold our future exploration strategy.
Lessons from Juno

• Understanding the atmospheric composition (enrichment of heavy elements) and the interior structure of the Saturn, Uranus and Neptune is essential.

• Comparing the planets with composition of multiple asteroid, dwarf planets, and comet populations is required.

• Planetary science and Exo-planet communities should meet together more often.
Planet Future Missions

- Juno w/Probes at Saturn, Uranus and Neptune
- Missions that can obtain a Survey of Small Body Volatiles (survey D/H and isotopes at many comets, dwarf planets, and asteroids)
- Eventually, Cold Sample returns from numerous categories and populations of Small Bodies
- Embrace the return to the moon as there are many unanswered questions on the Moon and Earth’s origin.
- Continue a balanced program exploring all planets, and satellites including ocean worlds