Survey of Open Science Questions on Outer-Planet Atmospheres

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Origin

- Get-together after the last OPAG meeting with Amy Simon-Miller, Kevin Baines, Leigh Fletcher
- Decided to outline the science needs for outer-planet missions
- Response to Survey Committee charge to “inventory top-level science questions that should guide flight programs and supporting research programs”

Development

- Orton agreed to start things (May)
- Fletcher developed an outline of
  - Over-arching science themes
  - Specific questions on each atmosphere
  - To be used only as a starting point
- Email sent out to many investigators in outer-planet atmospheres, both US and non-US
  - Requesting interest
  - Requesting interest in heading one of these papers

Outcome

- Several responses
  - Atreya, Baines, Coustenis, de Pater, Dowling, Edgington, Gulkis, Hartogh, Hofstadter, Huestis, Livengood, Martin-Torres, Marty, Morales-Juberias, Owen, Sayanagi, Stallard, Wong, Yung
- Expressions of interest in “helping”
- No one jumped in willing to be the lead writer of one of these papers
- Independent efforts
  - Atreya: paper on probes
  - Hofstadter: paper on Uranus and Neptune missions and general science
  - Both include specific mission recommendations
  - Much independent work on Titan, so not included in this effort

Questions regarding format

- Orton is currently doing the writing and still getting responses to June solicitations
- Possibly one white paper per planet
- But there are several over-arching questions involving similar themes in each planet, so a single paper may be more appropriate
- Does not address specific missions
- Bagenal request that Orton head *another* white paper on need/requirements for robust ground-based support program - more likely to be included as a part of this paper (these papers)

Overarching issues: Vertical Coupling

- How are energy, momentum and gaseous composition connected/transported between various layers in the atmosphere ?
  - Related to questions such as the depths of the zonal winds
  - How is the 'classical-view' of upwelling zones and subsiding belts reconciled with the emerging view from eddy momentum fluxes that the opposite is true
  - Studies of lightning distribution and power may provide access to the deep troposphere to support this study
  - What is the connection between the neutral atmosphere and the charged environment of aurorae/magnetospheres?

Variations in Time

- Snapshots of the gas giants from spacecraft and from the ground are important,
- But to understand atmospheric dynamics we need to watch the evolution of (a) discrete features such as storms, convective instabilities, waves, polar vortices; and (b) seasonal phenomena.
- Need regular coverage across the spectrum of winds (of jets and vortices) to see how they change, particularly in response to thermochemical changes observed in the IR and visible changes in color.
- The EJSM team called this a global climate database to better inform radiative-dynamical models.

In-Situ Sampling by Probes

- In situ sampling of required to
  - resolve any long-lasting discrepancies from remote sensing studies for CHON compounds
  - measure noble gases and other species not accessible to remote sensing but providing vital constraints on solar system formation scenarios.
- Complemented by deep MWR sensing of O/H and N/H ratios to determine the deep cloud-inventory of all the gas giants.
  - Oxygen is still the holy grail on all these giant planets.

Nature of Clouds and Hazes

- Huge uncertainties in aerosols and clouds plague the analysis of the near-IR, thermal-IR, photochemistry: large roles in
  - shielding photolysis of certain molecules
  - radiative-climate models (particularly via their influence on tropospheric heat budget).
- Need to know the true altitudes of the tracers in wind tracking
- Center-to-limb studies over multiple wavelengths and comparative planetology of clouds and hazes might pin down some sort of consistent model for clouds on gas giants.
  - Reconciliation of cloud properties derived from different spectral ranges from the near-UV to the IR.
  - Changes in aerosol vertical structure and chromophore content (chemistry) in tandem with variations in PH_3, ortho/para H_2, temperature, spectrally-identifiable ammonia clouds on Jupiter (and Saturn)?

Laboratory Studies

- Development of comparable dynamical phenomena in geophysical fluid dynamics experiments.
- Reconciliation of absorption coefficients for different bands of important gases (e.g. PH_3).
- Plethora of lab experiments needed at the low temperatures and pressures relevant to the outer planets.
- NB: Independent white paper on laboratory studies (Dalton), appears to be flowering, so we're likely to contribute to that effort without generating an independent paper

Jupiter - 1

- POLAR HAZES: How do aerosols in the polar regions differ from other latitudes? Can we explain their entrainment at high latitudes? How does photochemistry and auroral energy deposition influence the polar hazes? The 3D distribution of hydrocarbons and stratospheric hazes could yield insight into stratospheric dynamics and chemistry at all latitudes.
- GLOBAL UPHEAVALS: What causes the emergence of plumes and instabilities on quasi-periodic intervals, and how does it lead to (and maintain) the coloration of the belts and zones? Long-term studies of these and a wealth of other time-variable phenomena?
- STORMS: What is the three dimensional structure of Jovian storm systems, what causes the onset of red coloration/strengthening? What maintains the circulation of these storm systems against dissipation?

Jupiter - 2

- VERTICAL COUPLING: How would contrasts in NH_3 and H_2O seen at depth from microwave sounding manifest themselves in regions of the atmosphere accessible through remote sensing at shorter wavelengths? How is energy transported by wave motions?
- BULK COMPOSITION: Can the Galileo probe results be reliably extrapolated to (a) other locations on the planet and (b) with depth to the deep interior?
- MULTI-YEAR STUDIES: To what extent has the long-term appearance of Jupiter (visibly, chemically, thermally) changed over time? Or is the belt/zone structure constant and invariant?

Saturn - 1

- HYDROCARBONS: What is the seasonal modulation of the stratospheric hydrocarbon distribution, relation to radiative climate models, photochemistry models. Reconcile photochemistry of C_2H_6 and C_2H_2 with the observations.
- VERTICAL COUPLING: What is the relation between the fine-scale 5_m structure and the smoother appearance at visible and thermal wavelengths? Do 5_m clouds have counterparts at other altitude levels?
  - Does wave activity viewed at 5_m have a counterpart higher-up (e.g. through mid-IR and visible observations)?
- WAVES: How is energy transported by wave motion within and between atmospheric levels, specifically via motion associated with Saturn's SAO, but also vertical waves observed in stellar occultations and RSS profiles? Why are Saturn's slowly-moving thermal waves ephemeral compared with those on Jupiter? What effect do these wave have on the atmosphere?
- EXOGENIC SOURCES: What is the rate of influx of ring and other exogenic materials into the atmosphere, and what is there relation with chemistry at a variety of altitudes?

Saturn - 2

- SEASONS: What effects does the seasonal variation of insolation have on (a) chemistry and the distribution of gaseous constituents; (b) aerosols and the para-hydrogen distribution which may be linked via aerosol catalysis; (c) temperatures and the stability against convection and large scale-atmospheric transport? What is the effect of the rings on modulating the climate response and the chemistry? Will the summer polar stratospheric vortex move to the northern pole as it emerges into spring? Are the tropospheric hotspots at each pole (and their hurricane-like features) persist through the coming decade?
- HEXAGON: Will the hexagonal wave remain fixed in the System III Voyager reference frame, thereby indicating Saturn's true rotation rate? What is the vertical structure of the hexagon, what is driving and maintaining it, and why is there nothing as permanent at the south pole (where only ephemeral polygonal waves have been observed)?
- BULK COMPOSITION: Can we reconcile remote sensing results for the D/H, N/H, C/H, $^{12}C/^{13}C$ ratios with in situ measurements? What is the noble gas and oxygen abundances, and the $^{15}N/^{14}N$ ratio?

Saturn - 3

- CLOUDS AND HAZES: What is the tropospheric cloud inventory, and what are the different cloud compositions? How do the hazes vary with season? What could be masking the signature of ammonia ice from the spectra (i.e. sedimentation, photochemical products)? What is producing the haze material? What is the relationship between observable clouds and lightning discharges?
- UNDERSAMPLED REGIONS: What is the stratospheric temperature and composition above the mbar level (i.e. better coverage and spatial resolution for limb sounding, submm sounding, RSS, occultations, etc.)?
- Importance of non-LTE effects? What is the relation between radio, microwave observations at depth with infrared observations?
- INTERIOR STRUCTURE: Requires close-in measurements of the gravity and magnetic field to determine the rotation rate of Saturn, constrain core size? Does the magnetosphere rotate at a different rate to the planet?
- EQUATORIAL OUTBURSTS: What is the source of the strong equatorial upwelling responsible for elevated PH_3, sub-equilibrium para-H_2, elevated aerosol content, etc? What changes when we see the emergence of Great White Storms?

Uranus - 1

- GENERAL COMPOSITION: What is the variation of the chemical and aerosol composition with latitude, altitude and time?
  - Can these be explained thermochemically or photochemically?
- INTERNAL HEAT: Is the internal heat flux really zero?
- METEOROLOGY: Why does the Uranian troposphere and stratosphere appear more sluggish (i.e. less convective outbursts) than the other gas giants?
  - Or would 5_m observations reveal a dynamic atmosphere below the cloud-tops as they did on Saturn?
  - What is the nature of small-scale convection on Uranus?
  - What is the 3D structure of the large-scale circulation?
  - What could account for the stratospheric variability in emission observed by Spitzer?

Uranus - 2

- POLES: Does Uranus have distinct polar vortices or hotspots in the same way as the other gas giants? If not, why not?
- SEASONS: With the largest orbital obliquity of any of the giant planets, how does seasonal insolation variations affect the temperature and composition of the atmosphere? Requires long-term monitoring of the atmosphere across a variety of wavelengths.
- BULK COMPOSITION: We have only C/H and D/H measured on Uranus, so in situ sampling, microwave radiometry and radio observations (for N/H, O/H, S/H) would be vital constraints on Uranus' formation.
- DEEP INTERIOR: Can the planet have a liquid or frozen-water interior?
- MAGNETOSPHERE: At what point in the atmosphere is the magnetic field generated, and how?

Neptune - 1

- INTERNAL STRUCTURE: Where is the origin of the magnetic field? What is causing its huge tilt relative to the spin axis, and is there any manifestation in the atmosphere from this alignment?
- POLAR HEATING: Is Neptune's hot south pole a generalized vortex, similar to Saturn's?
  - If so, is there then a comparable cold vortex at Neptune's northern winter pole, like there is at the summer?
  - If the south pole is warm enough for methane to leak into the stratosphere, what is the meridional variation of methane and how does this impact the composition and chemistry?
  - What causes the hot stratospheric spot near Neptune's pole to wander from the geographic pole and in longitude over time?

Neptune - 2

- WINDS: What makes Neptune's jet streams stronger than anywhere else in the solar system? (This will probably require sampling of winds beneath the clouds, for which entry probes will be necessary.)
- DEEP COMPOSITION: Just as for Uranus, the deep composition of Neptune is poorly constrained and we would benefit immensely from entry probes.
- STORMS: What confines bright cloud activity to the two mid-latitude bands? How do the bright bands evolve with time, and what is the link to the temperature and composition of the bands? What are the clouds made of, and what is the vertical structure?