

Planetary Atmospheres

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Abstract. Observation, characterization, and understanding the atmospheres of our neighboring planets and moons in the solar system provide essential inputs for addressing broad science goals. These goals include identifying the conditions that are favorable for producing and supporting biological activity, managing the effects of human activity on the Earth's atmosphere, and planning and evaluating observations of extra-solar planets. Here we review the current state of knowledge, pose key science questions, recommend enhancements in the research infrastructure for investigation of planetary atmospheres, and propose new space missions with specific science objectives.

Executive Summary

Observing, characterizing, and understanding planetary atmospheres are key components of solar system exploration. A planet's atmosphere is the interface between the surface and external energy and mass sources. Understanding how atmospheres are formed, evolve, and respond to perturbations is essential for addressing the long-range science objectives of identifying the conditions that are favorable for producing and supporting biological activity, managing the effects of human activity on the Earth's atmosphere, and planning and evaluating observations of extra-solar planets.

Current knowledge, based on very few observations, indicates that the planets and moons in the solar system have diverse atmospheres with a number of shared characteristics. Comparing and contrasting solar system atmospheres provides the best near-term means of addressing the broad scientific goals. Additional space missions with specific atmospheric objectives are required. At the same time, investment of additional resources is needed in the infrastructure of observation and interpretation of planetary atmospheres.

Current observational characterization of planetary atmospheres is roughly comparable to what had been learned about the Earth's atmosphere after the first rocket and satellite measurements in the 1950s and 1960s. From telescope observations and planetary missions we have determined the principal atmospheric constituents and the altitude profiles of pressure and temperature. We are able to classify the atmospheres of many of the larger solar system planets and moons into four groups:

1. Nitrogen atmospheres (Earth, Titan, Triton, Pluto)
2. Carbon dioxide atmospheres (Venus, Mars)
3. Hydrogen gas giants (Jupiter, Saturn, Uranus, Neptune)
4. Thin atmospheres, with three subgroups:
 - Rocky surfaces (Mercury, Moon)
 - Volcanic (Io)
 - Icy surfaces (Europa, Ganymede, Callisto)

Interpretative studies of radiative transport and collisional processes in the atmospheres of Venus and Mars have helped us understand the "greenhouse effect" and the impact of continued release of carbon dioxide into the Earth's atmosphere. Characterization of the composition of the atmospheres of the gas giants provides guidance about how planets and their atmospheres originate and how to interpret observations of extrasolar planets. Exploration of the current and historical abundance and state of water in the atmospheres, surfaces, and subsurfaces of Mars, Europa, Venus, and the Moon will provide important clues about photochemical stability of planetary atmospheres and the production of prebiotic chemistry.

Unfortunately, even with an increasing volume of observational data, planetary atmospheres are still grossly undersampled. For example, at the relevant altitudes in the atmospheres of Mars and Venus we have no observations of the

minor chemical species (HO_x , ClO_x , SO_x) that models suggest are responsible for the stability of CO_2 atmospheres (as a result of catalytic recombination of CO and O_2) and for catalytic depletion of ozone in the Earth's atmosphere. Thus far we have sampled only a portion of the atmosphere of Jupiter. Without knowledge of the abundance of the heavier elements C, N, and O in the deep atmosphere, little can be said about whether the gas giant planets reflect the initial elemental composition of the solar system. The nitrogen/hydrocarbon atmospheres of Titan, Triton, and Pluto can provide important clues about photochemical formation of complex organic molecules in the early atmosphere of the Earth.

In addition, investigations of the Earth's atmosphere show that significant unpredictable variations occur on time scales of hours, vertical scales of a few kilometers, and horizontal scales of hundreds of kilometers. The atmospheres of many planets reveal structure and variation with respect to latitude, longitude, and season. Everything changes with solar cycle. Atmospheric models are very complicated. Many of the underlying chemical and physical processes are still poorly characterized. We think that we can produce useful explanations, but we do not have the data needed to ensure confidence that models can make quantitative predictions.

Four key questions/science themes were identified by the panel:

- *Understanding Atmospheres.* The historical attempts to understand planetary atmospheres have emphasized identification of the underlying chemical and physical processes responsible for the many fascinating observations. It is appropriate that the focus should now shift toward comparative interpretation of what the atmospheric observations and discoveries on multiple planets can teach us about broader scientific goals.
- *Learning by Exploring Planets and Moons.* Atmospheres are different each time we look at them. All future planetary mission campaigns should include explicit atmospheric components. Increased availability of observing time for planetary astronomy is essential on ground-based and near-Earth space-based telescopes.
- *Providing the Required Research Infrastructure.* Visiting planets is only one of the objectives. Lasting value comes from analyzing, interpreting, and using the data to establish broader implications, supported by independent programs for laboratory experiments, fundamental theory, modeling, and reanalysis of historical observations.
- *Assimilating Space and Planetary Science with Earth Science.* From our near neighbors in the solar system we hope to acquire additional hints about our origins and steps we should take to preserve our life-supporting environment. Better coordination between Earth science and space and planetary science can contribute to shared science goals, and justification and mobilization of additional funding resources for both disciplines.

The recommendations of the Planetary Atmospheres Community Panel fall into two broad categories. Recommendations that apply to multiple planets include establishing a mechanism for secure funding for analysis and interpretation of mission data, access to space- and ground-based telescopes dedicated to planetary observations, and creation of a new initiative for Comparative Understanding of Planetary Atmospheres. Recommendations for specific planetary missions with atmospheric goals include three Jupiter mission concepts, a Mars atmospheric explorer mission, a Post-Cassini/Huygens atmospheric/surface mission to Titan, and concepts for Neptune/Triton missions. Venus missions are also needed, but are not described here, under the assumption that they will be covered by the Venus community panel.

Other issues discussed by the panel included the public fascination with planets and the issue of international collaboration. Planetary observations make good news and well-watched television. Unfortunately, atmospheres look too much like chemistry and plasma physics. Other than the Jupiter impact of Shoemaker-Levy 9, neat colorful pictures are rare. U.S. citizens are better educated and intelligent than we suppose. Atmospheric scientists can do much more to explain why what we do is interesting, understandable, and important. The European and Japanese space agencies are launching capable planetary missions and planning future ones. A high level of coordination with these efforts is needed in order for the U.S. program of solar system exploration to reach its ambitious science goals.

REPORT

1. Current Knowledge and Key Science Questions

1.1. Introduction to planets and atmospheres

This document focuses on Planets, defined as the large objects orbiting the Sun: including Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto, along with their associated moons and companions.

The specific emphasis is on Atmospheres, defined as the interface between the planetary interior and the interplanetary medium: beginning with the top cm of the planetary surface; including atoms, molecules, ions, electrons, and cloud particles bound by the planet's gravitational field; also including planetary magnetic fields; and extending to the limit of the planet's non-gravitational influence on the interplanetary medium.

It is generally believed that the atmospheres of the small "rocky" planets and moons (e.g., Earth, Venus, Titan, etc.) are relatively young, having been created largely by outgassing as the surface cooled following planetary accretion; supplemented by later additions from impacting meteoroids, asteroids, and comets; and depleted by gradual escape of light elements to space. The "giant" or "gaseous" planets (Jupiter, Saturn, etc.) consist mostly of an atmosphere that is thought to roughly reflect the initial condensation of interplanetary atoms, molecules, and dust. Significantly, we know of only one planetary atmosphere with a large fraction of molecular oxygen, which is believed to have been formed on Earth by photosynthesis.

The surfaces and atmospheres of most planets and moons in the solar system receive more energy from external sources (usually sunlight and solar wind, supplemented on moons by tidal forces) than from upwelling from the planetary interior (e.g., original accretion energy and decay of radioactive elements). In general, the temperature of the planetary surface, and the altitude profile of temperature in the atmosphere, are controlled by the absorption of energy from the sun, reflection of visible radiation back to space, infrared emission by the surface (and clouds, if any), which is partially absorbed by the atmosphere, and eventually reemitted to space. This radiative transport problem defines the “greenhouse effect,” the understanding of which is essential to predicting the impact of the increasing carbon dioxide abundance in the Earth’s atmosphere resulting from combustion of carbon as an energy source for human activity.

1.2. Goals and objectives

The principal goals and objectives of the investigation of planetary atmospheres are briefly outlined below.

- Understanding the origin, history, composition, motion, and stability of planetary atmospheres: including formation during planetary accretion, by surface outgassing, or post-accretion deposition; modification of top-surface and atmospheric composition by external energy and mass sources; vertical and horizontal transport; clouds, winds, and storms; and loss of mass to space by surface ejection or exospheric escape.
- Characterizing the chemical and physical processes responsible for import of energy and mass from the sun and the interplanetary medium, response of atmospheres to external inputs, and release of energy and mass back to space.
- Identifying key observables for future planetary space missions and near-earth telescopic observations.
- Comparing the diverse planetary atmospheres in the solar system to learn what each can teach us about the others; to better understand the potential impact of human modifications of the Earth’s atmosphere; to characterize the processes in the atmospheres or top surfaces that could generate molecules of prebiotic significance; and to identify what signatures might be useful for characterizing the atmospheres of extra-solar planets.

1.3. Who studies planetary atmospheres?

Three communities of scientists collaborate in the investigation, understanding, and interpretation of planetary atmospheres. “Observers” record atmospheric “data” using direct- sampling instruments on planetary probes, remote sensing instruments on Earth-orbiting satellites and planetary orbiters, and ground-based spectrometers, radar facilities, and telescopes. “Modelers” attempt to explain atmospheric observations and make predictions about which future observations would have the greatest impact. They use simulations based on microscopic processes that hopefully are well known from laboratory investigations, but if necessary, plausible numerical parameters are inferred by reproducing field

observations. “Laboratory investigators” quantitatively characterize the underlying microscopic processes.

1.4. How we observe planetary atmospheres

Most observations of planetary atmospheres are derived from remote sensing. Many of these are from ground-based telescopes, although these observations are subject to limitations imposed by atmospheric transparency and seeing. Airborne, earth-orbiting and near-earth instrument platforms supplement the ground-based observations by accessing parts of the planetary spectra unavailable to ground-based observers; they can also provide spatial resolutions not bound by atmospheric seeing and not achievable through adaptive optics technology in ground-based telescopes. Near-planet remote-sensing observations that are enabled by interplanetary missions fill the important niche that not only accesses the entire spectrum but also achieves the highest possible spatial resolution. The high spatial resolution of interplanetary instruments provides horizontal discrimination of field parameters such as temperature and cloud opacity, and it enables vertical resolution through sensing of the planetary limb. Near-planet spacecraft also access geometries not available from the earth, e.g., high phase angles of illumination.

In-situ observations of planetary observations also access limited regions of the atmosphere but provide a means to measure properties that are not possible through remote sensing, such as spectrally inactive constituents or portions of the atmosphere that are too deep to be accessed by remote sensing. They can also achieve vertical resolutions usually unachievable from remote sensing,

1.5. How we understand planetary atmospheres

Below we list a sequence of questions that illustrates the roughly historical progression of observation, inference, and understanding in the study of planetary atmospheres.

- What is the Nature of the Observables?
 - Assignment and measurement of strength and line widths of spectroscopic absorbers and emitters
 - Measurement of cloud reflectivity as a function of wavelength, emission angle, and solar incidence angle; determination of Bond albedo
 - Cloud reflectivity/absorptivity measurements by atmospheric probes
 - Determination of thermal output, bolometric and in spectral regions of well-mixed constituents for thermal structure
 - Temperature vs pressure measurements by atmospheric probes
 - In-situ chemical assessment of gases and particulates (e.g., mass spectrometry, gas chromatography, spectroscopy, specific heat/acoustic wave speed) of gases and particulates
 - Local wind speed measurements by time-lapse imaging of clouds
 - Wind speed component detection by Doppler experiments on atmospheric probes

- Radio occultation of spacecraft signals, visible/uv occultation of stellar signals
- Radio reflection and ionospheres
- What are the Energy Sources?
 - Sunlight
 - Internal heat and tidal forces
 - Solar wind
 - The role of planetary magnetic fields
- What are the Underlying Chemical and Physical Processes?
 - Radiative emission, absorption, scattering, and transport
 - Particle impact excitation, dissociation, ionization, and scattering
 - Neutral and charged chemical reactions
 - Excited state quenching and energy transfer
 - Coagulation, condensation and sedimentation of particulates
 - Molecular and eddy diffusion
 - Large-scale vertical and horizontal wind generation
- What are the Numbers?
 - Atmospheric composition and thermal structure
 - Intensities of atmospheric ultraviolet, visible, and infrared emitted and scattered light, including X-ray and microwave/radio-frequency radiation
 - Solar spectrum
 - Composition of the solar wind
 - Rates and cross sections
- Why do Observables Vary in Space and Time?
 - Solar cycle and coronal mass ejections
 - Winds, waves, and transport
 - Seasons and global patterns
 - Storms and lightning
 - Atmospheric regions: The “spheres”
- What can be Learned from Systematic Observations?
 - Expose vulnerabilities and uncertainties in atmospheric models
 - Learn about possible signatures of “interesting” atmospheres on extra-solar planets
 - Long-term changes due to human perturbation (ozone depletion, global climate change)

- Predict sporadic short-term interference with human technology (space weather)

In the earliest stage we attempt to explain the macroscopic observables, such as colors of aurorae being due to atomic and molecular emissions and that an ionized atmosphere can reflect radio waves. In the second stage we infer what sources of energy could produce the observed perturbations of the atmosphere. Next we attempt a microscopic description of the specific processes that could be used to construct a quantitative model. But the model will not work unless we have accurate numerical values for the starting conditions, energy inputs, and the rate parameters for energy deposition and chemical transformation. As this microscopic local model begins to be trusted we back off from a local or point description and attempt to understand how variations in energy sources generate atmospheric dynamics. Finally we come to what atmospheric scientists tell the general public are the reasons why their field is important.

1.6. Specific needs by category and object

- Comparative Understanding Needs
 - Formation, evolution, stability, and structure of atmospheres:
 - * All: Non-thermal exospheric escape
 - * Venus/Mars: Stability of CO₂ atmospheres
 - * Giants: Planetary elemental composition
 - Atmospheric motion: coupling between atmospheric regions, vertical and horizontal transport, mixing, and diffusion:
 - * All: Origin of super-rotation
 - * Mars: Coupling of condensation and release of polar volatiles, dust storms, atmospheric dynamics, thermal structure, and chemistry
 - * Giants: Origin of long-lived powerful storms and the role of the latent heat of water
 - Planetary magnetic fields: differences between and implications of interactions of the solar wind with the atmospheres of planets with magnetic fields (e.g., Earth and Jupiter) compared to those without (e.g., Venus, Mars, Titan)
- Observational Needs
 - All: Repeated systematic observations: every 20 years is not enough
 - All: Signatures of winds and transport
 - All: Direct measurements of exospheric escape
 - All: Measurements of airglow emissions (UV, visible, IR, especially on nightside of Mars and outer planets)
 - All: Measurements of auroral emissions and correlation with the plasma environment
 - Venus/Mars: Minor species composition below 120 km

- Venus: Mid-level and surface winds
 - Venus: Middle-atmospheric cloud structure and variability
 - Giants: Elemental abundances of H, He, N, O, etc. in the deep atmosphere.
 - Giants: Measurements of deep atmospheric winds
 - Giants: Measurements of gravitational moments
 - Giants: Measurements of horizontal and vertical thermal waves
 - Giants: Measurements of horizontal winds over several scale heights
 - Giants: Measurements of birth and decay of large- and small-scale features: particulate, tracers, temperatures
 - Giants: Long-term measurements of horizontal winds
 - Giants: Long-term measurements transport tracers
 - Giants and Titan: Measurements of horizontal and vertical variability of temperatures, aerosols, cloud particulates, tracer gases
 - Giants and Titan: Horizontal and vertical variability of CH₄-derived constituents
 - Giants and Titan: High-precision abundances of isotopes
 - Giants and Titan: Characterization of seasonal and other external forcing
 - Jupiter: Measurements of auroral activity and correlation with solar wind
 - Jupiter: Measurements of polar regions: establishing the relationships between processes in the charged and neutral atmosphere, establishing the existence and maintenance of a polar vortex.
 - Titan: Temperature and chemical abundances in the troposphere and at the surface
- Modeling Needs
 - Venus/Earth/Mars/Titan: Are general circulation models evolving toward a unified description that explains how planetary parameters control energy and momentum budgets?
 - Venus: What can be learned from nightglow variability?
 - Earth/Jupiter: What can be learned from auroral emissions?
 - Titan: a unified description combining GCM, dynamics, and photochemical models.
 - Laboratory and Theory Needs
 - All: variability of non-Lorentzian line shapes with temperature
 - All: characterization of ice index of refraction spectra, both pristine and irradiated
 - Mercury/Moons: Trapping of volatiles in the top surface, radiation and impact induced chemistry and desorption

- Venus/Earth: Relaxation of O₂ excited states
 - Venus/Earth/Mars: Rate of CO₂(000) + O(³P) → CO₂(010) + O(³P)
 - Venus/Mars: Yields of O(¹S,¹D) from e + O₂⁺(v>0)
 - Venus/Mars: Energetic H/H⁺ collisions with O
 - Giants: Equations of state, solubility, and molecular diffusion in H₂/He at low temperature and high density
 - Giants: CH₄/CH₃/CH₂/CH photochemistry
 - Giants and Titan: Relaxation of CH₄ and hydrocarbon excited states, to characterize stratospheric non-LTE conditions
 - Giants and Titan: Quantum or empirical ground-state potential energy surface, rovibrational energies, and transition probabilities for individual visible and near-infrared transitions
 - Giants and Titan: measurement of low-temperature gas absorption coefficients in the visible and ultraviolet where quantum theory is intractable
 - Giants and Titan: shape and scattering properties of condensed particulates
 - Giants: non-Lorentzian line shapes in visible, e.g., K I, that are evident in brown dwarfs and probably influence the radiative transport process at depth
 - Jupiter: Ammonia isotopic fractionation
 - Jupiter: Determination of the full index of refraction for NH₄SH
 - Jupiter and Saturn: determination of the temperature dependence of the submillimeter line wing absorption by NH₃
 - Titan/Triton: CH₄ condensation and polyacetylene/nitrile photochemistry. More supporting laboratory measurements on aerosols, polymers, tholins and other organic material.
- Maintaining Future Capabilities
 - Justifying space missions
 - Justifying Research and Analysis (R&A) programs
 - Space telescope capabilities for planetary astronomy
 - Competition for time on large telescopes
 - Effective collaboration with Earth science programs
 - Coordinated collaboration with European and Japanese space agencies
 - Political support for NASA and NSF
 - Communicating with the public and Congress
 - Enhancing laboratory research
 - Career prospects in planetary atmospheres

2. Recommendations

The discussion above illustrates that planetary atmospheres are important, interesting, and complicated. We have learned quite a bit, but our partial understanding leads to many new questions. The following goals and themes may facilitate prioritizing the numerous science needs and mission possibilities.

- *Broad Science Goals.* Understanding how atmospheres are formed, evolve, and respond to perturbations is essential for addressing the long-range science objectives of identifying the conditions that are favorable for producing and supporting biological activity, managing the effects of human activity on the Earth's atmosphere, and planning and evaluating observations of extra-solar planets.
- *Understanding Atmospheres.* The historical attempts to understand the atmospheres of the Earth and other solar system objects have emphasized identification of the underlying chemical and physical processes responsible for the many fascinating observations. After decades of exciting discoveries, and with anticipated future discoveries of no less interest, it is appropriate that the focus should shift toward comparative interpretation of what the atmospheric observations and discoveries on multiple planets can teach us about broader scientific goals.
- *Learning by Exploring Planets and Moons.* Atmospheres evolve, move, change, and vary from place to place. A single observation is never enough. Planning of all future planetary mission campaigns should include explicit atmospheric components with specific scientific objectives emphasizing the need to fill gaps in our understanding. For example, the current strong Mars program is weak in atmospheric observations. The resource of ground-based and near-Earth space-based telescopes has been very productive historically, but observations of solar system atmospheres are currently not rated highly by time allocation committees, nor are current priorities for future space telescopes.
- *Providing the Required Research Infrastructure.* Visiting planets is only one of the objectives. Lasting value comes from analyzing, interpreting, and using the data to establish broader implications. Funding for post-flight analysis and interpretation of mission data needs to be reserved in advance and secured against escalation of hardware costs. In addition, well-funded independent Research and Analysis (R&A) programs, including laboratory experiments, fundamental theory, modeling, and reanalysis of historical observations, are essential contributors to the impact of the study of planetary atmospheres.
- *Assimilating Space and Planetary Science with Earth Science.* The broad science goals for planetary science are actually inward looking. From our near neighbors we hope to acquire additional hints about our origins and the steps we should take to preserve our life-supporting environment. In contrast, the current organization of research programs at NASA and NSF suggest a strong distinction between Earth science and space and planetary

science, demarked by a boundary about 50 km above the Earth's surface. While this may reflect a perception of separate communities of researchers, it presents a barrier for effective communication, contribution to shared science goals, and justification and mobilization of funding resources for both disciplines.

The majority of the Decadal Survey Community Panels address individual solar system objects, or collections thereof. For many of these, the atmosphere is only one of several important topics of scientific interest. In contrast, the Planetary Atmospheres Community Panel is one of the few that focus on science themes that apply to many solar system objects.

Below we have grouped our recommendations into two categories: (1) programmatic and infrastructure improvements that apply to multiple solar system objects and (2) recommendations for specific planetary missions. The first group also includes issues that are broader than atmospheres, but are included here because we are passionate about them. In the second group we include three missions to Jupiter (the Giant Planets community panel joined with Planetary Atmospheres), an atmospheric mission to Mars (the Mars panel is concentrating on surface missions), an atmospheric/surface mission to Titan, and concepts for missions to Neptune and Triton (these recommendations might be adopted by the Titan and Neptune panels). We had originally planned to suggest an atmospheric mission to Venus, but defer to the Venus panel that has a strong atmospheric emphasis.

2.1. Programmatic and infrastructure recommendations

Secure funding for mission data analysis and interpretation: Successful Solar System Exploration missions generate vast amounts of observational data, only a portion of which can be analyzed and interpreted within the mission duration. In addition, planned funding for data product generation and archiving, as well as analysis and interpretation, is often consumed in advance to cover escalation of hardware and operation costs. This problem has been avoided in part by the Discovery Program, in which DA is not included in the mission funding cap. However, Discovery Program guidelines of only 1-3% of Phase C/D is not adequate for missions having diverse instruments and science objectives, allowing only one or two investigations per year per instrument, and excluding the broader community of researchers. The problem is greatly magnified when the design and generation of mission data products are also underfunded.

A healthy R&A program is necessary for the definition of well-focused planetary missions and to provide the knowledge base needed to maximize the science return to cost ratio for those missions. Having completed the initial reconnaissance of the solar system (excepting Pluto-Charon), missions are no longer in the "let's see what is there" category and these programs are even more important now than in the past to mapping out the next phase of solar system exploration. The health of Planetary R&A programs is being eroded by the fact that they are the only means by which scientists can fund post-mission data analysis (after the conclusion of a modestly funded one to two year mission-specific data analysis program) and the body of mission data is growing rapidly. This is in stark contrast with NASA Astrophysics, which funds the Astrophysics Data Program

and Long Term Space Astrophysics Program for post-mission data analysis out of the OSS Data Analysis budget line.

RECOMMENDATIONS: Mission data product generation and archiving budgets should not be included in the mission cap. The budget should be justified separately and negotiated with both the mission and the NASA Planetary Data System and include margin. The requirement that Data Archive and Management Plans be developed and signed off prior to launch should be enforced. The quality of mission data products is the ultimate measure of mission success. Transparency, usefulness, and accessibility are critical.

- DA programs for every mission should not be included in the mission cap and should be funded at a level that reflects the complexity of the mission and its science objectives. A benchmark of several investigations per year per instrument should be used. DA programs should begin within a short period of time after data products are archived and available in the NASA PDS. These programs should extend for at least three years beyond the end of mission. All DA awards should be peer-reviewed.
- Planetary Data Analysis funding should be augmented to support the creation of a Planetary Data Program and a Long-Term Planetary Space Research Program. These programs would be parallel to the corresponding Astrophysics Data Program and Long-Term Space Astrophysics Program, funding planetary research utilizing data from all past planetary missions beyond their mission specific DA programs. This should also include planetary research using data from past astrophysics missions (explicitly excluded in the ADP and LTSAP). Funding levels of these programs should be equivalent to their Astrophysics counterparts. The purpose of this recommendation is in part to relieve DA pressure from R&A programs, therefore it is important that Planetary R&A program funding not be reduced or cancelled to pay for these new Data Analysis programs.

Dedicated telescopes for planetary astronomy: A major portion of our knowledge of planetary atmospheres comes from observations made from telescopes on the ground, on aircraft, or in near-Earth orbit. These telescopes provide opportunities for more scientists to participate in planetary research as well as for repeated systematic observations of how planetary atmospheres evolve.

In spite of this productivity, cost effectiveness, and growing telescope capability, observing time for solar system observations is actually becoming more difficult to acquire.

Requests for planetary observation time on large ground-based telescopes have very low approval rates. Time allocation committees (TAC) tend to be dominated by galactic and extra-galactic science interests. Requests for partial nights further reduce the approval prospects because they require extra TAC effort to schedule the remaining time. As deployment of adaptive optics and interferometry increases, the bias against planetary astronomy will get even worse. NASA controls only a small fraction of the large ground-based telescope assets: principally IRTF and one sixth of Keck.

The Hubble Space Telescope is viewed as a good platform for planetary observations and allocation of time is thought to be more balanced. In addition

to providing higher spatial resolution, observations from outside the Earth's atmosphere extend the achievable wavelength regions and permit the observation of faint objects near bright ones. Unfortunately, Hubble will be decommissioned as soon as it can be replaced. NGST appears to be targeted exclusively toward extra-solar-system observations. Issues include loss of ultraviolet and visible instruments and capability to track moving objects.

RECOMMENDATIONS:

- NASA should plan, launch, and operate a new Hubble-class space telescope with UV, visible, and IR imaging spectrometers and other instrumentation appropriate to planetary astronomy.
- NASA should increase its financial support for ground-based telescopes, including existing telescopes, and join consortia for new telescopes. Even telescopes as small as 2 m can be useful for planetary observations if they are equipped with capable instrumentation. One possible approach might be to create a new grant program for telescope instrumentation, through which a telescope consortium could request NASA funds for equipment purchases, in return for allocating a fraction of the telescope time for outside planetary observers. NSF has implemented a similar approach, the Telescope System Instrumentation program (TSIP), based on the recommendations in the National Research Council report *Astronomy and Astrophysics in the New Millennium*.
- Observing time should be allocated by open competitions, as is currently done by NASA for Hubble, Keck, and IRTF (and by NSF for NOAO, etc), but the emphasis should be on planetary science.

Comparative understanding of planetary atmospheres (CUPA): Current knowledge indicates that the atmospheres of the Earth, planets, and moons are quite diverse; yet share a number of characteristics, from which each can teach us something about the others. Comparing and contrasting planetary atmospheres provides the best near-term means of addressing the broad scientific goals of identifying the conditions that are favorable for producing and supporting biological activity, managing the effects of human activity on the Earth's atmosphere, and planning and evaluating observations of extra-solar planets.

In contrast to this unifying "comparative approach" the communities of atmospheric scientists, the "sections" of professional societies, and the organization of programs at research funding agencies (NASA and NSF) tend to emphasize a separation into three separate categories: planets and moons, space physics (Earth upper atmosphere above 50 km), and atmospheric chemistry (Earth lower atmosphere below 50 km). There is also a fourth category called astrophysics, whose research topics resemble atmospheric science, but at much lower or much higher densities and temperatures. These separations have understandable historical foundations, based in part on differences in observational techniques, and amplified by independent justifications used in competition for research funding. At the same time, these separations actually weaken both scientific productivity and prospects for research funding for all atmospheric scientists.

NSF has developed approaches for attracting increased funding for multidisciplinary programs without requiring reorganization of existing program

management organizations. Recent examples are the Information Technology Research (ITR) and Nanotechnology programs. NASA's "Living with a Star" initiative has been similarly successful.

RECOMMENDATIONS:

- NASA and NSF should establish a multi-agency multi-program multi-year long-term initiative for Comparative Understanding of Planetary Atmospheres (CUPA).
- Additional funding from Congress would be required, which the benefits of the comparative theme would justify. CUPA is a way to explain the importance of R&A programs.
- The initiative must be supported by strong endorsement from NAS/NRC. The planetary atmospheres research community must contribute to the campaign.
- Annual program solicitations should be issued with coordinated proposal evaluations. The resulting grants would be administered by the most relevant existing program.
- The solicitations might have an annual theme, but the main criterion should be that the research be truly "comparative."
- Much can be learned from the largely unsuccessful 1998 attempt to launch a similar joint NASA/NSF program. The justification was weak, lower atmosphere program managers were not convinced, and the solicitation required proposers to focus on Mars rather than explicit comparisons between planets.

2.2. Mission recommendations

Jupiter Microwave Sounder: As discussed elsewhere in this report, the composition and dynamics of the deep troposphere of Jupiter (down to pressures of ~ 100 bars or more) are central to many of the questions we have about the giant planets. The abundances of oxygen and nitrogen, and the large-scale circulation pattern are of particular interest: the former placing constraints on models of planetary and atmosphere formation, and the latter telling us about how deep atmospheres organize themselves in response to solar and internal heating.

Microwave observations are particularly sensitive to the reduced forms of oxygen and nitrogen (water and ammonia), allowing centimeter to decimeter wavelength data to tell us their abundances in the deep, well-mixed portion of the Jovian troposphere. Furthermore, microwave remote sensing can collect observations globally, allowing us to determine horizontal and vertical variations in abundances which in turn can be used as tracers to infer the general circulation of the atmosphere and the nature of convective and cloud-forming processes. Microwave sounding is therefore a uniquely suited remote-sensing technique to address key questions about giant planet atmospheres.

While in-situ measurements (such as provided by an entry probe) can more directly address some of the above questions, there are scientific, technological, and financial reasons to fly a passive microwave sounder as a precursor to a

full-up multiprobe mission. Scientifically, probes are limited in number and cannot achieve global coverage. Entry probes can also be targeted more effectively if we already have some critical information on the deep atmosphere. From a technological point of view, conditions in the deep atmosphere must be known before a probe's design (particularly the communication system) can be optimized. Finally, a multi-probe mission is much more challenging and expensive than a relatively simple radiometer.

To achieve its objectives, the microwave sounder will most likely have to fly within Jupiter's radiation belts on a polar trajectory, allowing it to avoid confusion from synchrotron emission while sampling all latitudes. A study made for a Discovery Mission proposal has determined that a fly-by trajectory can achieve all the science objectives, while minimizing cost and the radiation hazard. Furthermore, even within the constraints of a Discovery mission, supporting instruments can be flown to provide more information on the interior of Jupiter, the cloud-top dynamics, and the fields and particles environment. This microwave mission serves as a model for future missions to all of the gas giants, particularly since a fly-by trajectory may allow multiple planets to be observed with a single spacecraft.

Deep penetration probes to determine elemental compositions of giant planet atmospheres: The Galileo Probe data on the elemental abundances of Jupiter has challenged our views of the formation of the giant planets and the subsequent evolution of their atmospheres. Contrary to expectations, the Probe measurements revealed, for the first time, that in the deep well-mixed regions of Jupiter's atmosphere, "all" of the measured heavy elements, C, N, S, Ar, Kr, and Xe are enriched relative to their solar proportions by a factor of 2-3. A plausible explanation is that the heavy elements were delivered to Jupiter largely by icy planetesimals. The volatiles containing many of these elements can be trapped in amorphous water ice only at temperatures of 30 K or lower. This implies that the planetesimals must have their origin in the pre-solar nebula nascent interstellar cloud. Another hypothesis argues for the trapping of the volatiles in clathrate hydrates. The two scenarios predict vastly different abundances of water, hence the importance of the oxygen elemental ratio on Jupiter.

Unfortunately, the elemental abundances measured by the "single" Galileo Probe may or may not be representative of the entire planet. To complicate matters, the Probe also entered a meteorologically anomalous region known as a (5 micron) hot spot, where downwelling is expected to alter the distribution of the volatiles, especially the condensable volatiles. Moreover, the abundance of the carrier of the heavy elements, water, continues to be a mystery. The water mixing ratio in the deep well-mixed part of the atmosphere—where it should be uniformly mixed—could not be measured. This is due to the fact that in the hot spot where the Probe made its measurements, the region of the uniformly mixed water must lie well below the deepest level probed, 21 bars, since the water vapor mixing ratio was found to be still increasing at this depth.

If the first of the above hypotheses of the heavy element enhancement on Jupiter is correct, the water abundance, hence the oxygen elemental ratio, must have an enrichment similar to that of the other heavy elements. The clathrate-hydrate scenario predicts at least three times greater enrichment in the oxygen

elemental ratio relative to the other heavy elements. Still other scenarios may be possible.

In order to understand the formation of Jupiter and the evolution of its atmosphere, it is thus imperative that ALL heavy elements, including oxygen, be determined accurately in the deep well-mixed regions of Jupiter at several different latitude/longitude locations, and for comparison on Saturn. A comprehensive understanding of the formation of the giant planets and their atmosphere would be crucial also for modeling the formation of the extrasolar planets and the origin of their atmospheres.

In addition to the elemental abundance measurements, it would be important to study the dynamics of the deep atmosphere, including the questions of atmospheric stability and the depth to which the zonal winds extend and how they vary with latitude at great depths.

In summary, cleverly instrumented deep multiprobes into Jupiter, followed by Saturn, and eventually, Uranus and Neptune are recommended. In addition, it would be highly desirable to explore the possibility of precursor missions that could determine by remote sensing at least the N and O elemental abundances, as they would help with much more intelligent and sophisticated instrumentation and planning of the comprehensive elemental abundance measurements with the multiprobes (see the Jupiter microwave sounder description above).

Jupiter Polar Orbiter: A number of processes in Jupiter's atmosphere are centered in its polar regions, which have not been scrutinized directly since the high-latitude flyby of Pioneer 11 in 1973, although oblique views of polar areas have been obtained by Voyager, Galileo and Cassini spacecraft. In addition, a number of atmospheric properties that were to have been determined by Galileo were not accomplished because of telecommunications problems, and were addressed only briefly by the Cassini flyby.

One goal of this mission is to determine the relationship between the properties of Jupiter's electromagnetic field, together with its intrinsic time variability and that forced by solar wind variations, and the auroral discharge that is present in its upper atmosphere. In order to accomplish this, in-situ measurements of Jupiter's electric and magnetic field would be coupled with remote sensing of its auroral properties from X-ray and ultraviolet through near-infrared emission, primarily from hydrogen.

A second goal of this mission is to determine the relationship between the charged and neutral portions of Jupiter's atmosphere. A relationship exists between auroral discharge, the energetics of charged particles that are constrained by the magnetic field, and properties of the neutral atmosphere. Among the properties of the neutral atmosphere are the growth of particulates in the stratosphere at high latitudes and the existence of a region of high temperature at high altitude. Portions of the latter are characterized by anomalous abundances of hydrocarbons. Thermal measurements of temperature, a spectroscopic inventory of constituents in and out of these "auroral-related" regions, and a determination of the concentration of aerosols and their properties from ultraviolet/visible/near-infrared imaging/spectroscopy within the well-known polar haze are needed. These should include limb sensing to determine stratification of temperatures, chemicals and aerosols, to within scale-height resolution.

A third goal of the mission is to determine the meteorology and neutral energetics of the polar regions, and elsewhere on the planet. The first glimpse of the details of polar circulation were obtained by Cassini imaging and revealed surprising organization. Better details are possible with observations that are not nearly so oblique. In addition, there is a possible polar vortex that is characterized by a cold air mass that may be detectable in both the troposphere and the stratosphere but cannot be characterized well from ground-based or spaceborne facilities because of the limitations of diffraction-limited angular resolution. It is not known whether the entire polar region that appears to entrain aerosols is subject to a general upwelling, as is true for other relatively cold regions in Jupiter (its zones and anticyclonic vortices). Measurements of waves from limb sensing will also measure the amplitude and characteristic length of vertically propagating waves. These properties can also be measured at lower latitudes, as well, where the relationships between vertical winds, temperatures, aerosols, condensates, and other minor constituents (e.g., PH_3 and para- H_2), can be determined down to the size of the deformation radius and better, and tracked in some cases as a function of time.

Such a mission would be a valuable adjunct to either a multi-probe mission or to the Discovery "Inside Jupiter" mission, if either were to be approved. However, it is of sufficient merit to stand on its own. It may be somewhat greater in cost than a Discovery-class mission.

Mars Atmospheric Explorer: In many ways Mars is the most Earth-like of solar system objects and has much to teach us about the origin of life-supporting environments and possible significant signatures that might be observed on extra-solar planets. Especially intriguing are previous observations that show the presence of water in the current Martian atmosphere and polar caps. In addition, the observed surface topography provides hints that liquid water may have been present in the past and that substantial amounts may lie buried below the surface. Understanding the historical evolution of the Martian climate, and especially the history of water, requires detailed knowledge of the Martian atmosphere and the coupling between the surface and the atmosphere. Sustained repeated observations are needed to follow the geographical differences and diurnal, seasonal, and solar-cycle variations.

Unfortunately, the Martian atmosphere is the least studied of the 3 terrestrial planets. We have insufficient information to compare the chemistry of the Martian atmosphere with those of Earth and Venus. Yet, the Martian atmosphere is likely to be affected by chemistry to a greater degree than any other. Some key science questions are listed below.

- CO_2 is photochemically unstable on Mars, yet it exists. The postulated chemical explanation involves photolysis of atmospheric water, but we have no observations of the altitude profiles of the key minor chemical species (H_2O , H_2O_2 , HO_2 , OH , H , H_2 , O , O_2 , O_3 , CO , and CH_4) in the middle atmosphere.
- The interaction of the Martian atmosphere with the solar wind and the escape rate of the atmosphere have never been investigated observationally. The evolution of the Martian climate and the history, stability, and loss of

water are tightly coupled with the rates of exospheric escape of H and O atoms. We have some information about the H-corona but know almost nothing about the exospheric density and rate of escape of O atoms.

- The relationships among condensation and release of polar volatiles, dust storms, atmospheric dynamics, thermal structure, and chemistry are likely to be important. Almost nothing is known about the actual wind speeds in the atmosphere of Mars, other than from model simulations. Limited information about the Mars thermospheric density is being derived from aerobraking measurements by Mars Global Surveyor (1997-1999) and Mars Odyssey (2001-2002). These data show a tight coupling of the Mars lower (0-80 km) and upper (80-200 km) atmospheres. Both hydrostatic (inflation/contraction of the entire atmosphere with the seasons and dust events) and dynamical (tidal waves propagating up from the surface to the lower thermosphere) coupling processes (and their impacts) have been observed.

Recommendations for components of a Mars Atmospheric Explorer would include:

- An orbiter (similar to Pioneer Venus) with ion and neutral mass spectrometers as well as UV, visible, and IR spectrometers to measure the composition of the upper atmosphere, ionosphere, and exosphere, including dayglow and nightglow. A Fabry-Perot instrument could measure wind speeds in the upper atmosphere. It would also be useful to measure the charge-transfer depletion of O^+ ions from the solar wind, and the corresponding fast neutral O-atoms.
- Sacrificial descent probes for mass spectrometry measurements in the middle atmosphere.
- Balloons for lower atmosphere measurement of wind speeds as well as mass spectrometry.

Mars atmospheric science currently has a very low priority in the U.S. Mars Exploration Program agenda and upcoming NASA spacecraft missions. Some of the key science questions outlined above will be addressed by the upcoming Nozomi and Mars Express missions (2004-2005). A strong U.S. program of future missions could make especially valuable contributions by observing the Martian atmosphere near solar maximum (2010-2012).

Post-Cassini/Huygens atmospheric/surface mission to Titan: Ground-based and satellite observations of Titan are powerful means to study many of the processes occurring in this exciting planetary object. They are not, however, a substitute for in-situ measurements. Although the Cassini/Huygens mission to Titan will undoubtedly bring valuable answers to current problems regarding the satellite from 2004 and for 4 years, it will by the same token give rise to new questions that will require further exploring by more sophisticated missions in the future.

Thus, with the heritage of the Voyager, ISO and Cassini/Huygens data, new mission(s) to Titan, affording higher spectral and spatial resolutions, greater sensitivity and longer time spans could address items that remain unknown with regard to the atmosphere and the surface inventory of the satellite.

In the atmosphere, the nature and the spatial distribution of condensed particulates (such as aerosols, clouds, solids, etc) especially in the lower atmosphere need to be defined with emphasis on their involvement in the general organic chemistry. The degree of complexity attained by the latter and its connection with prebiotic chains remains to be established. The major composition, temperature structure and methane cycle are to be investigated by Cassini; there may however be seasonal variations that require further observations (a season on Titan is 7.5 yrs). The photochemistry, dynamics and circulation processes in the atmosphere require long-term measurements with technologically improved instruments aboard a future mission.

One of the most important remaining uncertainties with respect to Titan is, however, the nature of its surface. Even if the Cassini/Huygens probe will explore the ground, this study is limited to only one location. We have, however, indications that the landscape on Titan is variable and even with complementing observations from the orbiter, all the different facets of the surface material will not be investigated by Huygens. Hence, while the Cassini/Huygens data will provide clues as to where one should be looking, we will undoubtedly require in the future a mobile lander (balloons, aerobots, airplanes, helicopters, or other airborne platforms have been suggested) with laboratory capacities to investigate the composition of the surface and the sub-surface of Titan at different locations (preferably more than two). If such a probe could be combined with the capability to measure the tropospheric properties (as defined in the previous paragraph), then a sophisticated orbiter could be dispensed with, provided there is some means of relay to the Earth made available.

Neptune and Triton: In spite of (perhaps due to) Voyager's success at Neptune and subsequent studies with HST, many questions about Neptune remain unanswered.

- Atmospheric dynamics and structure: What powers the winds, and why are the winds and thermal structure similar to those of Uranus, though the internal heat sources differ? How deep does the zonal structure go? NEED: visible imaging and thermal mapping at various phase angles with scales down to 10 km; occultations of radio telemetry signals to probe atmosphere down to ~ 2 bar.
- Atmospheric chemistry: What is the composition of discrete features (bright and dark), and of the atmosphere as a function of altitude? NEED: UV occultations to measure density, scale height, temperature and composition; compositional mapping at near-IR wavelengths.
- Planetary interior and magnetic field environs: Why are the magnetic fields much more asymmetric in ice giants than in gas giants? NEED: measurements of magnetic field and magnetospheric particles at a variety of latitudes and longitudes.

Short of exploring Pluto, exploring Triton may provide our best opportunity to examine the surface and atmosphere of a Kuiper Belt Object analog. Open questions regarding Triton include:

- Atmospheric structure and composition: What is Triton's atmospheric composition and structure, and how has it changed since Voyager? NEED: radio occultations for atmospheric size/structure; high phase and high-resolution (100-300 m) limb imaging for hazes/plumes; UV occultations (density, scale height, temperature, composition); atmospheric sampling (fly-through).
- Surface geology and composition: Is there evidence for "recent" solid-state convective activity in an icy mantle? How does composition vary between/within surface features? What causes geologic structures on Triton's surface? Has the geyser distribution changed since Voyager? Have atmospheric changes modified the surface? NEED: UV to near-IR global imaging (< 100 m); high-resolution imaging (10-30 m) of selected locales; thermal (50 and 100 microns) mapping; global 1-km imaging spectroscopy at 1-5 microns with R=300.

Numerous questions persist about the Neptune rings and small satellites: Are the ring arcs of Neptune a "major ring system waiting to happen"? Is a resonant model for arc stability correct? If not, how do arcs remain stable? Do Neptune's inner satellites show the effect of extreme tidal stress? NEED: low-phase 100-m scale imaging of arcs to find embedded bodies; high-phase 1-km scale imaging to detect new rings/arcs and to characterize ring/arc morphology; spectroscopic capability to determine composition.

Missions to Neptune to address these questions would include the following:

- Neptune orbiter: The orbiter is the core of the mission, providing a remote sensing platform, in-situ probes of the magnetic field and environs, and primary data links. An integrated imaging package would include: visible imager, IR imaging spectrometer, and UV imaging spectrometer. Other remote sensing devices are a thermal IR spectrometer and a microwave radiometer. Space physics detectors might include a magnetometer (and perhaps other instruments). Radio science instruments would also be necessary.
- Atmospheric multi-probe: Multi-probes are an essential part of an investigation of the deep (~100 bar) atmospheric structure and chemistry on Neptune. However, significant technology advances would be required to enable high S/N transmission from depth in a cost-effective manner. An optimal probe package would include a main probe (GCMS; sensors for temperature, pressure, and acceleration; solar and IR radiometers; nephelometer) and at least three mini-probes (GCMS; temperature, pressure, and acceleration sensors) to sample diverse atmospheric regions.
- Triton lander: A stretch goal would be a miniature surface lander to make in-situ studies of the satellite's lower atmosphere and surface geology/composition.

- Technological challenges: Recent studies indicate a Neptune mission with these capabilities is feasible given innovative technologies: high-power lightweight SEP and solar sails; qualified aeroshells; aerocapture; autonomous spacecraft communications; advances in miniaturization; lightweight power generation systems; temperature-tolerant electronics ($\sim 50\text{K}$); lightweight structures. These technology drivers are required for many outer planet missions; their solutions will be broadly applicable.
- Alternative Neptune and Kuiper-Belt Flyby: If the technology challenges prove to be too difficult to overcome in the next decade, an intelligently designed Neptune flyby mission might be able to address a significant fraction of the science objectives. It might also conclude with a flyby to a Kuiper-Belt object.

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