

**PLANETARY SCIENCE DECADAL SURVEY 2013-2023  
WHITE PAPER****Jupiter Atmospheric Science in the Next Decade**

**Leigh N. Fletcher**<sup>1\*</sup>, G. Orton<sup>1</sup>, T. Stallard<sup>2</sup>, K. Baines<sup>1</sup>, K. M. Sayanagi<sup>3</sup>, F. J. Martin-Torres<sup>1</sup>, M. Hofstadter<sup>1</sup>, I. de Pater<sup>4</sup>, S. Edgington<sup>1</sup>, R. Morales-Juberias<sup>5</sup>, T. Livengood<sup>6</sup>, D. Huestis<sup>7</sup>, P. Hartogh<sup>9</sup>, D.H. Atkinson<sup>10</sup>, J. Moses<sup>11</sup>, M. Wong<sup>12</sup>, U. Dyudina<sup>3</sup>, A.J. Friedson<sup>1</sup>, T.R. Spilker<sup>1</sup>, R.T. Pappalardo<sup>1</sup>, P.G.J. Irwin<sup>13</sup>, N. Teanby<sup>13</sup>, T. Cavalié<sup>9</sup>, O. Mousis<sup>14</sup>, A.P. Showman<sup>15</sup>, X. Liu<sup>16</sup>, M.B. Lystrup<sup>17</sup>, S. Gulkis<sup>1</sup>, T. Greathouse<sup>18</sup>, R. K. Achterberg<sup>19</sup>, G.L. Bjoraker<sup>20</sup>, S.S. Limaye<sup>21</sup>, P. Read<sup>13</sup>, D. Gautier<sup>22</sup>, D.S. Choi<sup>15</sup>, T. Kostiuk<sup>20</sup>, A.F. Nagy<sup>23</sup>, D. Huestis<sup>24</sup>, M. Choukroun<sup>1</sup>, I. Muller-Wodarg<sup>25</sup>, P. Yanamandra-Fisher<sup>1</sup>

<sup>1</sup>*Jet Propulsion Laboratory, Caltech, Pasadena, California, USA.*

<sup>2</sup>*University of Leicester, United Kingdom.*

<sup>3</sup>*California Institute of Technology, Pasadena, California, USA.*

<sup>4</sup>*University of California Berkeley,*

<sup>5</sup>*New Mexico Institute of Mining and Technology, Socorro, NM, USA*

<sup>6</sup>*NASA/Goddard Spaceflight Center, Greenbelt, MD, USA.*

<sup>7</sup>*Molecular Physics Laboratory, SRI International, Menlo Park, California, USA.*

<sup>9</sup>*MPI for Solar System Research, Germany.*

<sup>10</sup>*Department of Electrical and Computer Engineering, University of Idaho, Moscow, ID, USA.*

<sup>11</sup>*Lunar and Planetary Institute, Houston, USA.*

<sup>12</sup>*STScI/UC Berkeley,*

<sup>13</sup>*University of Oxford, Oxford, UK.*

<sup>14</sup>*Institut UTINAM, CNRS-UMR 6213, Observatoire de Besancon, Université de Franche-Comté, Besancon, France*

<sup>15</sup>*Department of Planetary Sciences, Lunar & Planetary Laboratory, University of Arizona, Tucson AZ, USA*

<sup>16</sup>*National Meteorological Center of China Meteorological Administration, China.*

<sup>17</sup>*Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA*

<sup>18</sup>*Southwest Research Institute, San Antonio, TX, USA.*

<sup>19</sup>*University of Maryland, Department of Astronomy, MD, USA.*

<sup>20</sup>*NASA Goddard Spaceflight Center, Greenbelt, MD, USA.*

<sup>21</sup>*Space Science and Engineering Center, University of Wisconsin, WI, USA.*

<sup>22</sup>*Observatoire de Paris, Meudon, France.*

<sup>23</sup>*University of Michigan, Ann Arbor, MI, USA.*

<sup>24</sup>*Molecular Physics Laboratory, SRI International, Menlo Park, California, USA.*

<sup>25</sup>*Space and Atmospheric Physics Group, Imperial College, London, UK.*

\* [Leigh.N.Fletcher@jpl.nasa.gov](mailto:Leigh.N.Fletcher@jpl.nasa.gov), 1-818-354-3518

**Supplemental Material Website:**

[http://www.atm.ox.ac.uk/user/fletcher/Site/Outer Planet Science Goals.html](http://www.atm.ox.ac.uk/user/fletcher/Site/Outer_Planet_Science_Goals.html)

**Contains a list of scientific investigations to answer some of the questions outlined in this document.**

## 1. Overview

The exploration of the gas giant Jupiter has played a pivotal role in the development of our understanding of the Solar System, serving as a paradigm for the interpretation of planetary systems around other stars and as a fundamental laboratory for the investigation of large-scale geophysical fluid dynamics and the many physiochemical phenomena evident on the gas giants. Yet, despite great success in the scientific investigation of Jupiter over four centuries of research, our characterization of Jupiter remains incomplete, with many fundamental questions unanswered. The thin atmospheric ‘weather-layer’, the only region accessible to direct investigation by remote sensing and in situ sampling, is only a tiny fraction of Jupiter’s total mass, yet it provides vital insights to the interior structure, bulk composition and formation history of most of our Solar System, as well as serving as the paradigm for extrasolar giant planets. *This white paper supports the scientific goals of Juno, advocates for expanded Jupiter atmospheric science as a crucial component of EJSM, and suggests continual studies of Jupiter from ground-based and dedicated space-based platforms, in addition to future entry probe missions.*

As we see it today, Jupiter is the end product of energetic accretion processes, thermochemistry, photochemistry, condensation processes, planetary-scale turbulence and gravitational differentiation. Its atmosphere is characterized by multiple latitudinal bands of differing cloud colors, temperatures, vertical mixing strengths and molecular composition; separated by strong zonal winds and perturbed by long-lived vortices, storms, polar vortices, local turbulent and convective outbreaks, wave activity and global changes to the large-scale circulation patterns. Although primarily composed of hydrogen and helium, Jupiter also contains significant amounts of heavier elements found in their fully reduced forms ( $\text{CH}_4$ ,  $\text{PH}_3$ ,  $\text{NH}_3$ ,  $\text{H}_2\text{S}$ ,  $\text{H}_2\text{O}$ ), providing the source material for rich and complex photochemical pathways powered by UV irradiation. The abundances of most of these heavy elements are enriched over the solar composition, providing a window into the past and a reflection of the primordial nebula material incorporated into the gas giants during their formation. Jupiter’s vertical structure is governed by the complex balance between energy deposition from the Sun, internal energy release and absorption and emission from molecular opacity sources. Indeed, the internal energy leftover from the formation makes Jupiter self-luminous, radiating away more energy than it receives from the Sun. Jupiter is the archetype for giant planets in our solar system, and its atmosphere is distinguished from those of Saturn and the Ice Giants by its larger mass, extended  $\text{H}_2$ -He envelope, small seasonal effects and the presence of multiple long-lived vortices. Studying Jupiter’s plethora of atmospheric phenomena, and the responsible physiochemical processes, also provide a window into the deep past of our Solar System and the mechanisms for the formation of giant planets.

This White Paper outlines key scientific drivers for Jupiter atmospheric science in the 2013-2023 time frame. The paper is organized into five themes from the macroscopic (global composition) to the finest spatial scales, focusing on the interrelationships between the deep convective interior, the dynamic troposphere, the middle atmosphere (stratosphere and mesosphere) and the upper atmosphere (ionosphere, thermosphere and the magnetospheric interactions with the objects within Jupiter’s complex system of orbiting bodies). Studies of the vertical coupling and the transport of energy, momentum and chemical tracers between these atmospheric layers, along with the temporal variability of the multitude of meteorological and climatological phenomena, should be used to develop a three-dimensional understanding of the gas giant.

## 2. Scientific Goals for Jupiter Exploration

The coming decade will see the development and launch of the Juno and Europa-Jupiter System Missions to Jupiter, based on recommendations of the first planetary science decadal survey. Even with the success of these missions, additional work will be needed for a complete understanding of Jupiter. The following five themes aim to capture the key scientific motivations for continued study of Jupiter's atmosphere in the target period and beyond.

### I. Formation and Evolution of Jupiter within our Solar System

Jupiter, the largest planet by mass, is thought to have retained the chemical signatures of the primordial nebula from which our Solar System formed, although thermochemically reprocessed via a series of chemical pathways over the intervening eons. Jupiter's global composition thus provides a unique window into the chemistry of the early solar system; and its elucidation remains one of the primary goals of Jovian exploration. Remote sensing has provided us with estimates of the atmospheric abundances of elements in their reduced forms (e.g. well-mixed  $\text{CH}_4$ ), but the primary reservoirs of many elements (nitrogen in  $\text{NH}_3$ , oxygen in  $\text{H}_2\text{O}$ ) require probing of the deep atmosphere below their respective condensation clouds to fully constrain bulk abundances (a key goal for the Juno mission). Jupiter is the only giant planet to have been sampled directly (by the Galileo Probe in 1995), but the unique meteorological conditions of the entry site (a region of strong subsidence, leading to depletion in volatiles) plagues the interpretation of some compositional results.

Galileo Probe results bolster the need for probes at multiple locations to provide a representative sampling. The relative enrichments of the simplest elements (C, O, N, S), along with isotopic abundances ( $^{12}\text{C}/^{13}\text{C}$ , D/H,  $^{14}\text{N}/^{15}\text{N}$ ,  $^{18}\text{O}/^{16}\text{O}$ ) and the abundances of noble gases (He, Ne, Ar, Kr, Xe, etc.) within Jupiter are vital to constrain (a) the mass of rocky or icy material attained by Jupiter during its accretion; (b) the size and composition of Jupiter's core and degree of homogenization with the extended molecular atmosphere; (c) the possible source-reservoirs of material (and the temperature of their formation) incorporated into Jupiter; (d) the possible timescales for the formation of the gas giants; and (e) the thermochemical pathways and cooling history of the planet in the billions of years since its formation (see, e.g. Atreya et al., 2003). Such measurements could help determine whether significant migration of planetesimals or planets occurred in the early solar system and reveal details of the structure of the solar nebula (including the presence of a "snow line." Furthermore, the bulk composition of Jupiter connects it directly to the nature (and potential habitability) of its extensive satellite system. As many of these elemental and isotopic ratios are inaccessible to remote sensing, in situ sampling by multiple probes (3 or more) is vital to complement the microwave remote sensing from Juno (see e.g. white paper by Atkinson et al. 2009). In addition, laboratory spectroscopic work at the temperatures and pressures relevant to the gas giants is a vital prerequisite for the interpretation of remote sensing data, particularly for the high pressures to be observed by Juno.

Several questions that Jovian exploration can answer are pertinent to planetary systems around other stars. For example, is the enrichment in oxygen sufficient to support current planetary formation theories, which require trapping of volatiles in ices or clathrate hydrates prior to accretion? Does a rocky core exist in Jupiter's deep interior and what is its mass? Can we understand the generation of Jupiter's complex magnetic field? What sources of energy determine the self-luminosity of Jupiter and the cooling history of the planet (phase transitions

and gravitational separation of H<sub>2</sub> and He)? Comparison of these fundamental properties (bulk composition, deep internal structure, thermal evolution) with the other giant planets has the potential to reveal the common principles responsible for the development of planetary systems that are suitable for life.

## II. Global Three-Dimensional Understanding of the Weather-Layer

As demonstrated by the unusual conditions met by the Galileo Probe, an understanding of the dynamics, chemistry and meteorology of Jupiter's 'weather-layer,' (here defined as the upper troposphere and condensation clouds and the stratosphere and mesosphere) is essential for the interpretation of bulk chemical abundances. Remote sensing over the past several decades has provided a wealth of information about processes at a number of discrete altitudes and particular regions. However, the crucial challenge for experiment and modelling in the coming decade will be the development of a fully global three-dimensional understanding of the observable atmosphere, and its connection to deeper levels. In particular, we must understand the mechanisms for the transport and mixing of energy, momentum and chemical species (tracers) vertically and horizontally, and how this system maintains the vertical temperature and cloud structures, stable zonal jet systems, super-rotating equatorial winds, giant vortices and global-scale meridional circulations (see, e.g., Vasavada and Showman, 2005). How can the 'classical view' of upwelling, cloudy, moist "zones" adjacent to subsiding, clear and dry "belts" be reconciled with observations of convective updrafts within the belts and horizontal convergence of momentum into the jets due to eddy momentum flux (Salyk et al., 2006)? What is the importance of moist convection, and what maintains the belt/zone contrasts in temperatures, cloud coloration/altitude and chemical abundances? What determines the altitude of the radiative-convective boundary (between 400-600 mbar, approximately) and the tropopause (100 mbar), and can convective overshooting move material through the cold tropopause? What is the three-dimensional structure of Jupiter's large anticyclonic vortices, what causes the colors of the clouds and their reddening, and the strengthening of their wind fields? What maintains the circulation of these storms against dissipation? What is the three-dimensional distribution of disequilibrium species (para-H<sub>2</sub>, PH<sub>3</sub>, AsH<sub>3</sub>, GeH<sub>4</sub> and CO)? Does Jupiter's zonal organization extend all the way to the poles (high latitudes to be observed by Juno) and exhibit cyclonic polar hotspots as on Saturn? What determines the scale of latitudinal organization on Jupiter, and sets the jet stream widths, locations and stability, and what makes them so different to those on the ice giants? This unresolved question is a fundamental geophysical fluid dynamics problem.

Moist convection, eddy momentum fluxes, turbulence, vertical wave propagation and frictional damping of dynamic motion are believed to play roles in shaping and maintaining the atmospheric circulation at a wide range of temporal and spatial scales, so *long-term* temporal monitoring of cloud formation and motion, temperature and wind fields, chemical evolution and other meteorological phenomena is required in the UV, visible and infrared. Individual "snapshots" of these atmospheric variables are not enough to constrain radiative, chemical and dynamical models. Instead, new missions should focus on monitoring the atmosphere over multiple timescales (see section V, below), either from orbiting spacecraft (EJSM and successors) or from a dedicated platform (e.g. from the ground or the dedicated orbiting facility).

Above the clouds, in the region of the atmosphere governed by radiative energy exchange and photochemistry, remote sensing is required to reveal the complex interplay between solar energy

deposition and middle-atmospheric dynamics. Lacking the strong seasonal forcing evident on Saturn, Jupiter provides a vital counter-point to Cassini's exploration of seasonal change on Saturn. Yet the processes responsible for the atmospheric inversion; heating and cooling; large-scale middle-atmospheric circulation and upper level aerosol production are thought to be common to all gas giants. We do not yet know if stratospheric oscillations of wind and temperatures like Jupiter's Quasi-Quadrennial Oscillation are common or rare on the gas giants, but observations of this phenomenon on multiple planets (and determination of the sources of the waves responsible for the QQQ) presents a valuable opportunity for a comparative study. High spectral resolution submillimeter spectroscopy should be used on EISM to provide our first estimates of winds in the middle atmosphere (from Doppler wind broadening of the lines) and to study the stratospheric abundance profiles of exotic species like HCN, CS, CO and H<sub>2</sub>O.

Infrared remote sensing and direct sampling with multiple probes (ten or more) or neutrally buoyant weather stations within, above and below the cloud layers are required to reveal the optical properties, chemical composition, vertical structure and radiative-dynamic influence of Jupiter's clouds, hazes and lightning activity. Such measurements address the question of how photochemistry and auroral chemistry influence haze production and hydrocarbon distributions. The polar stratospheric hazes are particularly intriguing, and we seek to explain (a) why the polar hazes appear to be asymmetric, (b) why they differ from mid-latitude and equatorial hazes; and (c) how they are entrained at high latitudes. Large uncertainties in the basic properties of the aerosol and cloud inventory plague the analysis of infrared spectroscopy, photochemical modelling and radiative-climate models. Furthermore, without knowledge of the true altitudes of the discrete cloud tracers used in wind derivations, our extrapolation of the Jovian wind fields both upwards and downwards may be substantially flawed. Remote sensing across a wide spectral range, combined with laboratory measurements, coordinated modelling efforts and, ultimately, in situ investigations, are required to uniquely determine Jupiter's cloud properties.

### **III. Coupling of the Deep Interior with the Observable Atmosphere**

Remote sensing and in situ sampling of the observable atmosphere, combined with measurements of higher-order gravitational and magnetic field moments, satellite tides and acoustic oscillations of the atmosphere, provide our only access to Jupiter's deep interior. These are our only method for determining the deep chemical inventory, the atmospheric structure below the clouds, the exotic conditions of the deeper interior (i.e. the nature of the phase transition between metallic and molecular hydrogen), the workings of the internal dynamo and the existence and size of a solid rocky core. The understanding of the dynamics deep inside the planet will require numerical modelling, and the next major challenge for general circulation models is to develop fully self-consistent models that link deep convection within the molecular interior with their observable manifestations (i.e. linking shallow weather-layer models based on the primitive equations with the convective models for the deep interior). Zonal winds are known to persist to at least the 20-bar level, but their ultimate depth is unknown. Sensing to the 100-bar level and deeper, in the microwave (Juno), with UHF radio occultations, via perturbation signatures in the gravitational field or tracking of deep entry probes at multiple locations (ten or more), could answer this vital question for dynamical modellers. But this must be done in tandem with development of competent numerical simulations and geophysical fluid dynamics experiments.

Juno will aid the investigation of the vertical coupling in the troposphere by searching for compositional gradients at depth, involving latent energy release serving as the driver for moist convection that organizes Jupiter's weather layer into its characteristic belt/zone structure. The role of moist convection in shaping thermal stratification is poorly understood, particularly with multiple condensates, but studies of the energy spectrum, depth and spatial distribution of convection-produced lightning may provide access to the deep troposphere to help answer this question. To what extent do thermochemistry and vertical eddy and convective mixing from the several-kilobar level influence atmospheric composition, such as the presence of  $\text{PH}_3$  and other disequilibrium species at cold upper tropospheric levels? Can the distribution of these species be used as tracers for this strong vertical transport? Is there a deep source of vertically propagating waves observed in temperature and wind fields at higher altitudes? How does the dark red/brown coloration of Jovian plumes, newly-strengthened storms (such as Oval BA) and 'global-upheavals' reflect the composition of the atmosphere below the cloud-decks? What is the spatial distribution of condensates (such as spectroscopically-identifiable ammonia ice), and what does this tell us about the spatial variability of vertical mixing from the deep atmosphere to the observable troposphere?

#### **IV. Interactions between the Neutral Atmosphere, Charged Upper Atmosphere and Jovian Planetary Environment**

Similar to the coupling between the accessible neutral atmosphere and the deep, bulk flow and composition of Jupiter, another key goal is to understand fully the connection between the observable atmosphere and (a) the high-temperature thermosphere; (b) the charged-particle environments of the ionosphere and magnetosphere; and (c) the immediate planetary environment of the complex Jovian system (rings, icy satellites, exogenic material, etc.). The key question is how the charged -particle environment of the upper atmosphere and magnetosphere modulates and influences the composition of the mesosphere and stratosphere, particularly in the polar regions that are influenced by auroral energy.

Jupiter's upper atmosphere is poorly characterized when compared with the lower, neutral atmosphere, and several fundamental questions common to the gas giants remain unresolved. Ionospheric/thermospheric temperatures are 2-4 times higher than can be explained by solar heating alone; both observations and models are required to distinguish between the responsible physical mechanisms (upwards transport of energy from the deep atmosphere by gravity waves, or equatorward transport of auroral energy by meridional circulations). What is the origin of the detailed morphology and energy redistribution responsible for the polar aurora, and to what extent is it influenced by solar wind and the polar plasma environment? What mechanisms differentiate the morphology and time scale of the response of UV (Lyman alpha) and near-IR ( $\text{H}_3^+$ ) from auroral related heating and perturbation of hydrocarbons in the neutral stratosphere?

Jupiter's atmospheric composition has been perturbed from that expected from thermochemical arguments alone by interactions with the external planetary environments. In the most extreme cases, asteroidal/cometary impacts (such as Comet Shoemaker-Levy 9 in 1994 and the impact of 2009) leave dramatic remnants of their collisions (shock chemistry leading to the presence of exotic stratospheric compounds, such as HCN, CS, OCS and CO). These events provide a rare glimpse of planetary accretion processes in action, but other processes must still be observed indirectly, such as the presence of oxygen compounds in the high stratosphere that have an

exogenic source (from ring material, or some interaction with the icy satellites, micrometeorite bombardment, etc.). In particular, material erupting from Io is channelled by the planet's magnetic field and may supply charged species to the upper atmosphere. Such observations of external influences have wide-ranging consequences for solar system evolution and interpretation of middle-atmosphere composition and chemistry on other gas giants.

### **V. Time-Variable Atmospheric Phenomena over a range of Temporal and Spatial Scales**

Giant-planet observations will enter a new era in the coming decade, as the focus shifts from analysis of individual 'snapshots' to studies of time-variant processes. A full understanding of this archetypical Gas Giant will require quasi-continuous coverage of atmospheric evolution, and new missions and ground-based observations must focus on monitoring atmospheric phenomena over a range of timescales from hours and days, to years and seasons, to create a Jupiter global climate database. Such a database is vital to constrain temporally-variant theoretical models, and serve as a test of the fundamental underlying physics and chemistry. Such observations were not possible on the fly-bys of Pioneers 10 and 11, Voyagers 1 and 2, Cassini and New Horizons, leaving considerable gaps in temporal coverage. Earth-based coverage can fill some of these, but fine spatial scales are difficult to observe. Galileo could not achieve this goal because of its severely compromised telecommunications. Dedicated planetary monitoring in the coming decade is vital to support short-timescale missions like Juno and EJSM.

Ground-based observations in the last two decades have revealed a wealth of time-variable phenomena, but the absence of a dedicated multi-wavelength monitoring campaign leaves the underlying mechanisms poorly understood. For example, what meteorological and dynamical phenomena determine the evolution of discrete atmospheric features (storms, vortices, convective instabilities, hotspots, polar vortices)? How are the wind fields and vorticity of vortices related to thermochemical changes, such as changes to the chromophore content (reddening), the emergence of spectroscopically identifiable ammonia ice or changes to the temperature, ortho/para ratio or other chemical species? Although the belt/zone structure has remained stable in the long-term, episodic cycles and disturbances can lead to significant changes to the banded appearance (albedo, colour, temperatures, opacity). What causes these quasi-periodic global upheavals (including South Equatorial Belt disturbances), outbreaks and the emergence of plumes and instabilities, and what are the long-term consequences for the atmosphere? Development of a better understanding of these 'climate oscillations' could provide information about the atmospheres basic state (i.e. the vertical structure beneath the clouds).

What are the sources, periods and power distribution of wave activity (e.g., 5- $\mu\text{m}$  hot spots, slowly moving thermal features, mesoscale waves, and various other Rossby and gravity waves) and how do they affect the dynamics - such as influencing the pumping of zonal jets, driving the Quasi-Quadrennial Oscillation, enabling the stratospheric meridional circulation and modulating the distribution of chemical species? How high do such waves reach? With its low  $3^\circ$  obliquity, do seasonal changes in insolation or solar wind modulate atmospheric composition? Do changing wind patterns influence the thermochemistry of the atmosphere, and how do such changes affect cloud coloration and molecular composition? What is the distribution and power of lightning, how is this related to wave activity and what does this tell us about moist convection below the cloud tops? What is the frequency of asteroidal/cometary impacts, and what are their long-term consequences on the Jovian atmosphere?

Jupiter should be monitored on multiple time scales with an instrumentation suite capable of providing comparable spatial resolutions across a broad spectral range (with the goal of horizontal resolutions of 20 km or less for mapping of clouds, temperature contrasts and chemical species). High spectral-resolution spectroscopy (or limb-sensing imaging) is required to resolve vertical stratification on scales at or better than the atmospheric scale height. It also requires recognition that contextual imaging of Jupiter over large spatial areas is important to interpret high resolution imaging of small, localized regions. The capability for high resolution temporal observations of bright, extended targets like Jupiter must be maintained in the post-Hubble era, particularly in support of visiting spacecraft (Jupiter is too bright for JWST instruments without special considerations/filters).

### 3. Conclusions and Recommendations

Our understanding of Jupiter's atmosphere has improved greatly in the past decades, but there is still a great deal to learn about the planet and its role in the formation and evolution of our solar system. The exploration of Jupiter, the archetypical gas giant, is central to our understanding of how our solar system formed and the fundamental processes at work within outer planet atmospheres, so we therefore make the following recommendations:

- Maintain and upgrade capabilities for observing outer planets (ground-based and space-based) across the broadest possible range of wavelengths from X-ray to radio.
- Complete the Juno investigation of Jupiter's deep troposphere and polar atmosphere with ground-based support (contextual studies in multiple wavelengths).
- Expand the EJSM science and payload requirements to support the fundamental Jupiter science goals outlined in this white paper.
- Create a dedicated platform for regular planetary imaging and spectroscopy (either ground-based or space-based, see e.g. white paper by Wong et al.) to characterize temporally evolving phenomena over a range of timescales.
- Ultimately, revisit Jupiter with multiple entry probes to refine internal composition and structure measurements (constraining formation models) and to probe Jupiter's deep dynamics and meteorology in regions inaccessible to remote sensing.

The final challenge will be to explain Jupiter's atmospheric structure and composition, from equator to pole and from core to the highest levels, based on the fundamentals of fluid dynamics, meteorology, geophysics, thermochemistry and photochemistry. A full understanding of Jupiter's atmosphere will serve as the 'Rosetta-stone' model for understanding gas giants in our own solar system, extrasolar planets (e.g. hot Jupiters) and brown dwarfs.

### 4. Further Reading

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