

Giant Planet Atmospheres

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Abstract

The giant planets, Jupiter, Saturn, Uranus, and Neptune, all have vibrant and dynamic atmospheres. The iconic belt–zone structure of Jupiter, together with the Great Red Spot, is instantly recognizable. Saturn, with its dramatic ring system and more muted atmosphere, is a formidable jewel in the Solar System. In the outer reaches, the pale blue Uranus and Neptune are found, worlds about which ultimately very little is known. The atmospheres of these planets are dominated by hydrogen and helium, and unlike the Earth, they do not have a solid surface. These differences generate inherently different types of atmospheres, but there are also similarities. For example, the condensation of water, which forms the familiar clouds on Earth, also occurs on the giant planets. Broadly speaking, the atmosphere can be divided into different regimes defined by their temperature gradients. In the troposphere, where weather occurs, the temperatures decrease as a function of increasing altitude as convection moves internal heat upward; the rising material expands and cools. Above this region lies the stratosphere, defined by a positive temperature gradient, where hydrocarbons are heated by ultraviolet radiation from the Sun (analogous to ozone heating in the terrestrial stratosphere), which also drives substantial photochemistry. This is followed by a mesosphere that cools as a function of altitude, a region that is ill-defined at the giant planets. Finally, the upper atmosphere connects to the space environment and is heated by both solar extreme ultraviolet light and auroral processes. The giant planets are energized both by internal heat and by solar heating. These energy inputs, along with the fast rotation rates of these planets, drive dynamics by establishing global circulation patterns and generating both waves and instabilities. They also drive chemistry within the atmosphere, which alters composition and can influence the temperature structure, particularly in the stratosphere. The atmospheres of these planets can be observed using telescopes on the ground and in space, which can reveal composition, dynamics, and long-term changes. Much of the detailed knowledge of these planets comes from spacecraft such as the iconic Grand Tour of Voyager 1 and 2 in the 1970s and 1980s, as well as the Galileo and Juno missions to Jupiter and the Cassini mission to Saturn. In the 2030s, both the European Space Agency's Jupiter Icy Moons Explorer (JUICE) mission and the NASA Europa Clipper mission will arrive at Jupiter, and momentum within the planetary science community is building toward a mission to Uranus that would arrive at some point in the 2040s.

Keywords: giant planets, atmospheres, Jupiter, Saturn, Uranus, Neptune, circulation, turbulence

1 Introduction

An atmosphere is a gaseous envelope confined by the gravitational forces of a body. From the very thin and unstable atmosphere of Mercury to the dense and vigorously churning atmosphere that envelops Jupiter, there is an extraordinary variety of atmospheres observed throughout the

Solar System. The nature of the atmospheres of the planets (and moons) in the Solar System is shaped by processes such as solar forcing, internal heating, and rotation rates, along with the way these planets have evolved since their formation some 4.6 billion years ago. The giant planets, Jupiter, Saturn, Uranus, and Neptune (Figure 1), differ from the terrestrial planets in that they do not have a distinct surface, have fast rotation rates, and are much larger and heavier. The sheer size of these planets means that the strong gravitational field can retain lighter species, and so the outer layers are dominated by hydrogen and helium.

The giant planets orbit far from the Sun and therefore receive little sunlight: Jupiter receives about 4% and Neptune 0.1% of the sunlight received on Earth. Despite this, the energy provided by the Sun plays an important role, especially in the stratosphere and the thermosphere. Here, photochemistry can drive heating and complex chemistry, which can exhibit strong seasonal behavior. The tilt of Jupiter’s spin axis is small, only 3° , which means it has very muted seasonal behavior, whereas the tilts of Saturn (27°), Uranus (97°), and Neptune (28°) are larger, making seasonal geometry important for the thermal structure and dynamics of the stratosphere and upper atmosphere, just as it is for Earth’s atmosphere.

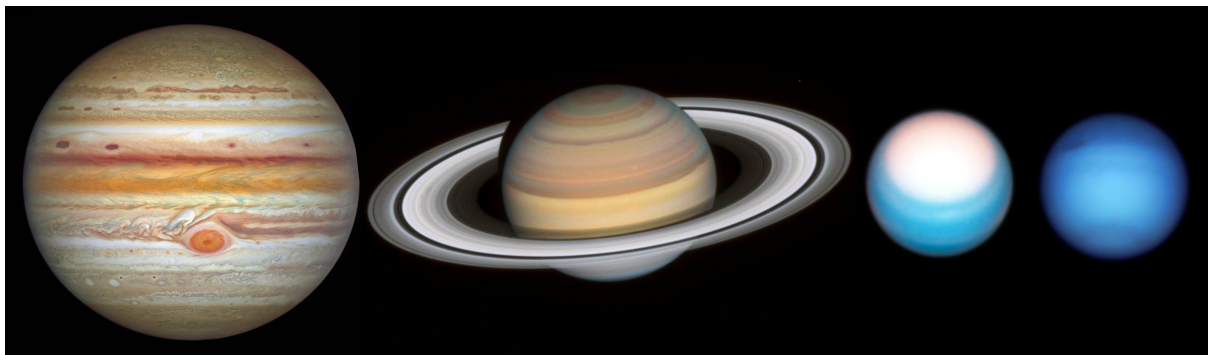


Figure 1: A giant planet family portrait: Jupiter, Saturn, Uranus, and Neptune, obtained with the Hubble Space Telescope in 2021. *Source:* NASA, ESA, A. Simon (Goddard Space Flight Center), and M. H. Wong (University of California, Berkeley) and the OPAL team.

The giant planets get their name by virtue of being very large, as summarized in Table 1, and they contain 99.6% of the total planetary mass. By virtue of their size and fast rotation rates, they also dominate the bulk angular momentum within the Solar System, accounting for $\sim 90\%$ of it, with Jupiter alone contributing $\sim 60\%$. Ultimately, their size, distance from the Sun, and composition provide constraints on the formation of the Solar System, and by understanding the atmospheres of these planets, they can be placed in the context of planetary evolution. The fact that observations of these atmospheres occur at a particular point on their evolutionary journey must also be considered. The distance at which a planet forms from its host star, the amount of mass that accretes in the protoplanetary nebula, along with its evolution as a function of distance from the star, are all important factors in determining what type of planet it will become millions or billions of years down the line.

For a protoplanetary nebula to retain any chemical elements, the temperature must be low enough for these species to condense into a solid state. Consequently, a planet that forms close to its parent star will experience high temperatures, and so volatile gases, such as water (H_2O) and methane (CH_4), are unable to condense and will escape the system. This means that only elements with higher melting points, such as iron, sodium, and silicates, can exist as solids. This explains why the terrestrial planets are rich in heavy elements but lacking lighter ones. Conversely, the farther a planet forms from its parent star, the more condensable species it can retain. The distance beyond which volatile icy compounds remain solid during the formation of planets is known as the *frost line*, which sits at ~ 5 AU (Jewitt et al., 2007).

The purpose of this article is to provide the reader with an overview of the atmospheres of the

giant planets, the processes that occur within them, and the general lexicon used to describe the relevant physics. Detailed mathematical descriptions are omitted here, and the reader is referred to more comprehensive works (Irwin, 2009; Sanchez-Lavega, 2011). Section 2 describes the basic vertical structure of these atmospheres, followed by the processes that can alter the atmosphere over long timescales in Section 3. Section 4 describes the basic dynamics of these atmospheres, including convection and turbulence triggered by instabilities. In Section 5, the gas giants (Jupiter and Saturn) will be discussed, followed by the ice giants (Uranus and Neptune) in Section 6. Finally, Section 8 contains a brief conclusion.

Table 1: Basic Physical Characteristics of the Giant Planets

Planet	Distance (AU)	Radius ($R_{\oplus}$)	Mass ($M_{\oplus}$)	Density (g cm^{-3})	Orbital Period (years)	Rotation (hours)
Jupiter	5.2	11.0	318	1.3	11.9	9.9
Saturn	9.5	9.1	95	0.7	29.5	10.7
Uranus	19.2	4.0	14	1.3	84.1	17.2
Neptune	30.0	3.9	17	1.6	164.8	16.1

2 Structure of an Atmosphere

An atmosphere can be divided into separate layers, delineated by distinct boundaries largely defined by the behavior of the vertical temperature profile, which in turn is driven by the different physical, dynamical, and chemical processes within each region. These regions are categorized in the same way on the giant planets as they are on Earth, as illustrated in Figure 2. This section summarizes these regions, moving upward in altitude toward decreasing pressures.

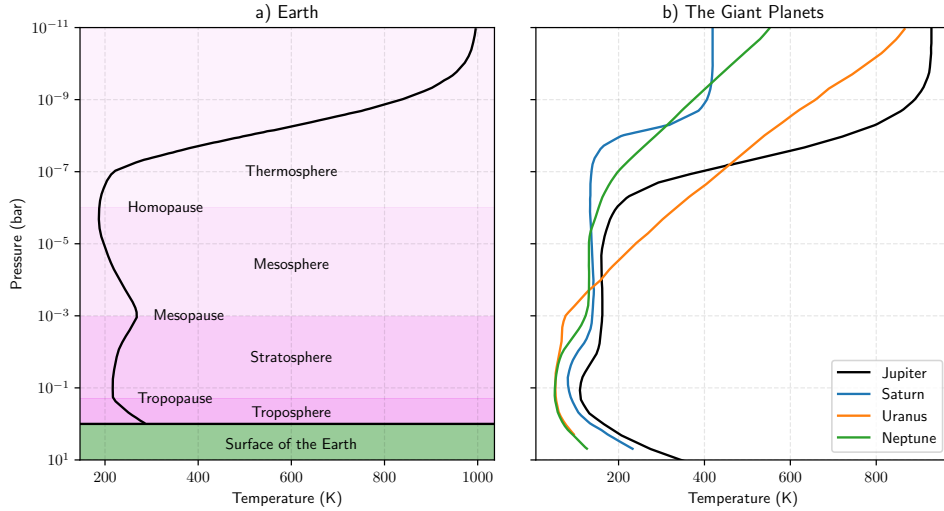


Figure 2: (a) The vertical temperature profile of Earth. (b) The temperature profiles of the giant planets. *Source:* Adapted from O'Donoghue and Stallard (2022).

2.1 Deep Interior

On Earth, the solid surface absorbs sunlight, which in turn heats the atmosphere at ground level. The giant planets do not have solid surfaces; however, there is still a source of heat available in the deep atmosphere. This is energy left from the formation of these bodies, and the continuing

slow collapse of these planets constantly releases heat, which warms their atmospheres at depth, through a process known as the *Kelvin–Helmholtz mechanism*. Jupiter, Saturn, and Neptune all radiate strong internal heat, whereas Uranus has very little to no internal heat (Pearl et al., 1990).

The basic interior structure of the giant planets is shown in Figure 3. The cores are thought to be made up of dense rocky materials, followed by an envelope of ices, metallic hydrogen and helium in a highly compressed environment, followed by the gaseous atmospheric envelope, containing mostly hydrogen and helium. The convective metallic envelopes of the cores are believed to be the origin of the powerful magnetic fields of these planets, and if the convection changes over time, the observed magnetic fields above the surface may also change on convective timescales. Therefore, these types of observations of secular change in the magnetic field can reveal long-term change deep inside the planet. Another way to sample the deep interior of a planet is to observe how the gravitational force exerted on a spacecraft flying close to the planet changes with position, revealing the *gravity moments* of the planet and, therefore, the internal structure. On Jupiter, such measurements by the Juno spacecraft have revealed that it has an extended region enriched in heavy elements (Wahl et al., 2017).

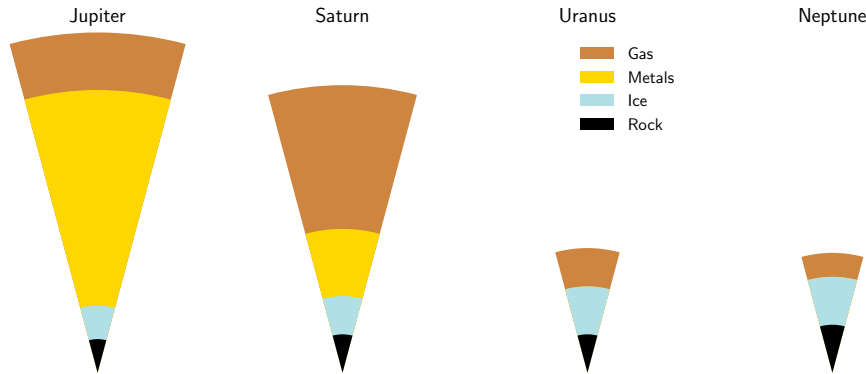


Figure 3: The basic interior composition of the giant planets.

2.2 Troposphere

The visual appearance of the giant planets is defined by sunlight reflected from the clouds and hazes in the troposphere, the lower part of the atmosphere. This is the weather layer, which is largely opaque and dominated by convection and turbulence. Internal heat provides a source of heat at low altitudes, and as parcels of air rise toward higher altitudes and lower pressures, the atmosphere cools, producing a temperature profile that decreases sharply with altitude. At the upper boundary of the troposphere lies the tropopause, the coldest part of a giant planet atmosphere.

In the troposphere, as species rise in altitude toward cooler temperatures, certain species will condense into solids and ices to form clouds, in a similar way to how water vapor rises in Earth’s troposphere and condenses to form clouds at higher altitudes. Convection in the presence of these condensable species is called *moist convection* (as opposed to *dry convection*). In the molecular nitrogen- and oxygen-dominated atmosphere of Earth, the lighter water vapor is naturally buoyant, whereas in the hydrogen- and helium-dominated atmosphere of the giant planets, the condensable species tend to sink, and therefore the formation of clouds becomes dependent on convection moving these molecules toward higher, cooler altitudes at which they can condense. At the giant planets, condensable species include water, ammonia, methane, as well as more complex molecules such as ammonium hydrosulfide (NH_4SH). The formation of clouds releases heat, which modifies the vertical temperature profile, because clouds can absorb

and scatter radiation.

In addition to clouds, higher-altitude hazes and aerosols can also form in the upper troposphere and lower stratosphere. *Hazes* are evenly dispersed and relatively uniform layers of small particles ($<1\ \mu\text{m}$ in size), whereas *aerosols* are more complex hydrocarbon compounds, products of methane photochemistry, that coagulate and condense. Aerosols can absorb significant amounts of solar energy (Zhang et al., 2015).

Uranus and Neptune, and to some extent Saturn, are shrouded in hazes in the lower stratosphere that obscure the planet, hiding the intricate weather occurring below. Strong convective events can lift clouds through this haze, making them visible. Neptune is strongly convective and has bright storms that appear and disappear on timescales of days and appear to be associated with the solar cycle (Chavez et al., 2023). On Saturn, during northern spring, a massive storm can develop, like a hurricane on Earth. The latest of these events occurred in 2010–2011 and was tracked by the Cassini spacecraft in orbit.

As the atmosphere becomes less dense with altitude, radiation becomes more efficient at transporting energy, as opposed to convection, and the boundary between these regimes is called the *radiative–convective boundary*, which occurs in the upper troposphere.

2.3 Stratosphere

Above the temperature inversion at the tropopause lies the stratosphere, in which the temperature increases as a function of altitude. This is driven by the absorption of solar extreme ultraviolet photons by hydrocarbons, predominantly methane, which can set off chains of complex photochemistry (Moses et al., 2000), generating species such as acetylene (C_2H_2) and ethane (C_2H_6), which in turn provide a source of radiative cooling. A similar temperature structure is seen on Earth, where absorption of sunlight by ozone (O_3) drives the heating. In other words, the temperature profile in the radiative domain of the stratosphere is governed largely by the solar-driven chemistry that takes place within it.

Because temperatures rise with altitude, vertical transport is strongly inhibited, and therefore the movements within it tend to be very slow. In the lower stratosphere, eddy, or turbulent, diffusion dominates, whereas in the upper stratosphere, where the mean free path of the atmosphere becomes larger, molecular diffusion becomes more important (Moses et al., 2007).

At high latitudes, auroral processes provide an additional source of energy that can produce heating and chemical reactions in the stratosphere, which can penetrate deep into the polar atmosphere (Sinclair et al., 2017).

2.4 Mesosphere

On Earth, as the ozone concentration decreases with altitude and carbon dioxide (CO_2) radiative cooling becomes more important, the temperature also decreases with altitude. This defines the mesosphere, containing the coldest temperatures seen in the telluric atmosphere. This decrease is not seen at the giant planets, or if it exists, the mesosphere is extremely limited. This is because the photochemical products of methane are distributed across a broad range of altitudes, reaching the homopause.

2.5 Upper Atmosphere

The upper atmosphere has two components: the neutral thermosphere and the charged particle ionosphere, produced by the ionization of the atmospheric constituents either by solar extreme ultraviolet (EUV) radiation or by charged particles delivered along magnetic field lines as part

of the auroral process (e.g., see [Achilleos et al., 2021](#); [Miller, 2021](#)). The lower boundary of the upper atmosphere is the homopause, at which eddy diffusion equals molecular diffusion. In other words, this is the boundary above which turbulent mixing is no longer dominant, and the species fall out according to their scale heights, which in turn are governed by their molecular weights. This means that the heavier elements (i.e., hydrocarbons) are distributed very close to the homopause, whereas lighter species, such as atomic and molecular hydrogen, can extend for thousands of kilometers at very low densities.

The upper atmospheres of the giant planets are all observed to be very hot, and it is unknown why. For Earth, the temperature of the upper atmosphere can be accounted for by solar EUV radiation. In contrast, the upper atmospheres of the giant planets are hundreds of Kelvins hotter than solar input alone can account for, and this discrepancy between observations and models has been dubbed the *energy crisis*. Suggested solutions are the global redistribution of auroral energy ([O’Donoghue et al., 2021](#)) and the breaking of gravity waves ([O’Donoghue et al., 2016](#)), but to date, no clear consensus exists.

2.6 Exosphere

The exosphere, delineated from the upper atmosphere by the exobase, marks the boundary between the atmosphere and the space environment. Here, the density is extremely low, and at the exobase the mean free path of a molecule is equal to that of the scale height.

3 Atmospheric Evolution

Once a planet is formed out of the protoplanetary disk, there are a number of processes that can change the composition of its atmosphere over long timescales:

- **Jeans’ escape:** The kinetic energy of a molecule can be increased by several processes within an atmosphere, the strongest of which are absorption of solar radiation and dissipation of gravity waves. A molecule with sufficiently large velocity can overcome the gravitational forces that confine it and escape the atmosphere. This process is clearly more efficient for lighter molecules. This escape can, over time, significantly alter the composition of terrestrial planets and moons, but since the giant planets are so massive, this process is unlikely to have significantly shaped the evolution of these systems since their formation.
- **Impacts:** For Earth, the bombardment by icy planetesimals delivered large amounts of water early in the history of the Solar System that radically changed the atmospheric composition and ultimately enabled the germination of life. This highlights how impacts can fundamentally alter atmospheric composition. The deep gravitational wells of the giant planets mean that they can easily attract small interplanetary bodies, such as comets and asteroids. The most famous example of this is the Shoemaker–Levy 9 impact on Jupiter in July 1994, where the large, fragmented comet (the largest fragment being 1.8 km in diameter) slammed into the southern hemisphere of Jupiter. These types of events can deliver new materials, eject materials already present, as well as drive localized chemistry.
- **Stellar Luminosity:** Both the evolution of a star and the process of planetary migration, where the orbital distance of a planet changes, can modify the amount of stellar flux that a planet receives. This in turn provides a variable energy input into a planet’s atmosphere, which can drive changes in Jeans’ escape and increase or decrease photochemistry, which can, for example, alter the stratospheric temperature profile.

- **Ionospheric Escape:** On Earth, the charged ionosphere is magnetically connected to plasma in the magnetic field. Since the pressure is high in the ionosphere compared to the magnetic tail downstream of the planet, there is a tendency for plasma to move from the ionosphere to the tail, known as the *polar wind*. A similar process is thought to occur at the giant planets, and modeling has suggested that $\sim 1.5 \times 10^{28}$ protons per second could be lost at Jupiter (Martin et al., 2020), which is a similar number of charged particles sourced from the volcanic plumes of Io (Bagenal, 1997).

4 Atmospheric Dynamics

The motion of an atmosphere is highly complex and can sometimes appear to be chaotic and random. This section will discuss the broadscale movements of the atmospheres of the giant planets and the general principles that can be applied.

4.1 Description of the Mathematical Toolkit

Consider a self-contained parcel of air in which energy does not leave or enter (i.e., it is adiabatic) and that has a constant entropy (i.e., it is isentropic). The foundations of circulation within an atmosphere can then be explored using the *ideal gas law*:

$$PV = nRT \quad (1)$$

where P is the pressure, V is the volume, n is the number density, R is the ideal gas constant ($R = 8.314 \text{ J K}^{-1} \text{ mol}^{-1}$), and T is the temperature. The fundamental driver of atmospheric circulation at the giant planets is the heating of the atmosphere at depth. A parcel of air deep in the atmosphere that is being heated will grow in volume and thus decrease in density. This change will drive the parcel to move upward in altitude toward lower pressures. As it moves upward, the decreasing pressures will act to further increase the volume, cooling it. Once the parcel has equilibrated with its surroundings in the upper troposphere, the reverse process can take place: a cold parcel contracts and moves toward higher pressures, completing the convection pattern of upwelling and downwelling.

The rate at which the temperature of an adiabatic parcel of air changes as a function of altitude is described by either the *dry* or *moist adiabatic lapse rate*, which refers to the absence or presence of condensable species within the parcel. These expressions provide a tool with which to calculate idealized vertical temperature profiles.

There are a number of equations that govern the motion of an atmosphere. The principal of these is the *Navier–Stokes equation*, which balances the forces exerted on a parcel of air, namely *gravity*, *friction*, *the pressure gradient*, and *centrifugal forces*. The pressure gradient is a result of differing pressures between different or within parcels of air, with the flow of air moving from low pressure toward higher pressures. The centrifugal forces give rise to *Coriolis forces*, which restrict movement of the atmosphere in the meridional (north–south) direction. Due to the size and fast rotation of the giant planets, the Coriolis force places strict limits on the meridional mixing of the atmosphere.

The *geostrophic equations* describe the motion of the atmosphere, which is dependent on the pressure gradient in each direction. This description requires the Coriolis force to be significantly larger than the pressure gradient force, and satisfying this condition is called the *geostrophic approximation*. The condition can be parameterized into a single number called *the Rossby number*, where values much less than one indicate that the Coriolis forces dominate. In these conditions, winds flow along lines of constant pressure, rather than from low to high pressures, as

would be expected due to pressure gradient forces. The rapid rotation of these planets suggests that this approximation holds.

The *thermal wind equations* relate the vertical shear of the geostrophic wind to the vertical temperature gradients. If the zonal velocity is known at a particular altitude (see Section 4.2), then this relationship can be used to derive the vertical wind field based on the observed vertical temperature gradients.

There are two types of vortices in an atmosphere: *cyclones*, which form over a region of low pressure, and *anticyclones*, which form over a region of high pressure. They have opposite senses of rotation, and the direction of motion is dependent on the hemisphere in which they appear. The most famous anticyclone is the Great Red Spot (GRS) on Jupiter. These can be characterized in terms of *vorticity*, which is a measure of rotational speed and is related to angular momentum, which is a conserved quantity. *Potential vorticity* is a related concept that is also conserved and that can predict the behavior of vortical flows as they evolve (e.g., change in size).

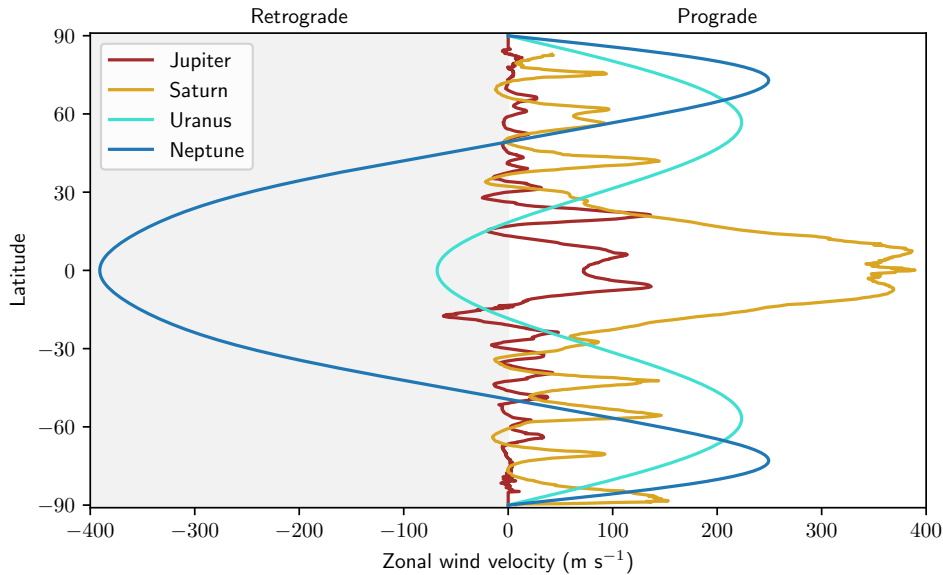


Figure 4: The observed zonal wind velocities on Jupiter (Porco et al., 2003), Saturn (García-Melendo et al., 2011), Uranus (Hammel et al., 2001), and Neptune (French et al., 1998).

4.2 Zonal Winds

The observed zonal (i.e., east–west) winds in the troposphere for the four giant planets are shown in Figure 4. These are derived from cloud tracking, observing the relative motion of clouds or other features between successive rotations. Observations have shown that these winds are very stable over time, and how these extremely strong winds can be sustained over very long timescales is not known. Their stability indicates that they are driven by internal processes rather than external solar forcing. The equators of Jupiter and Saturn have prograde (superrotating) zonal winds, whereas the equators of Uranus and Neptune have retrograde (subrotating) zonal winds. The strongest winds are seen on Neptune, followed by Saturn and then Uranus, all of which have faster winds than Jupiter.

On Jupiter, the zonal wind structure is present at great depth ($>10^5$ bar; Kaspi et al., 2023), suggesting that the observed winds may be a signature of processes that occur deep inside the planet. By using the thermal wind equation, the way the winds decay with height can be calculated, and on all four giant planets they become zero at ~ 4 scale heights above the cloud

tops. At Jupiter and Saturn, the peak velocities in the zonal flows coincide with the boundaries between belts and zones.

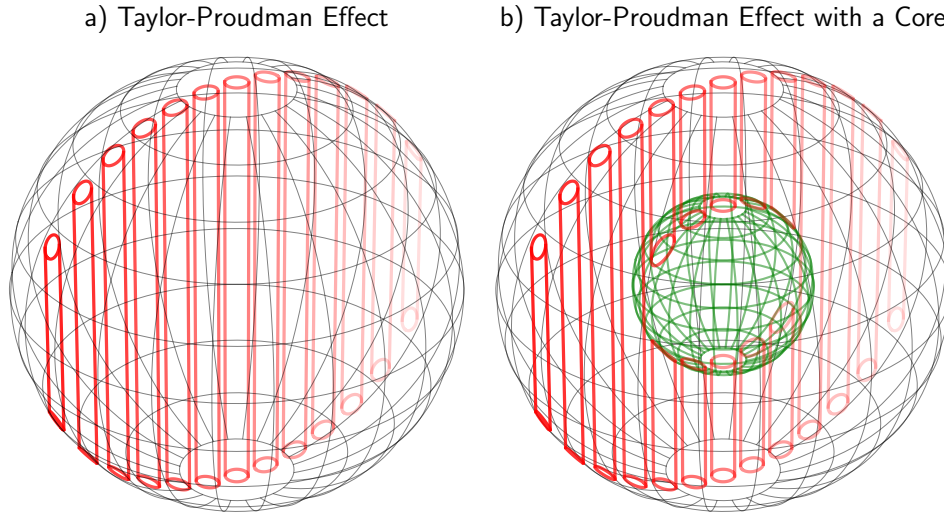


Figure 5: An illustration of the Taylor–Proudman effect of a rotating liquid sphere (black), with and without a core (green). The liquid tends to organize into rotating cylinders (red), with each cylinder rotating in an opposite sense compared to the one next to it. While cylinders occupy the entire volume of the sphere, only a cross-section is shown here for clarity. The presence of a core will disconnect the cylinders that emanate at high latitudes. This is known as the *deep model* of atmospheric dynamics.

4.3 Circulation Cells

The banded structure of Jupiter is nontrivial to explain, and it is helpful to first consider Earth. On Earth, the *Hadley cell* features upwelling from the equator and downwelling at midlatitudes ($\sim 30^\circ$ latitude), forming a closed loop driven by solar heating, known as *thermally direct circulation*. At around 60° latitude, warm air rises and is transported toward the pole, where it cools and sinks, completing the loop. Between the Hadley cell and the *polar cell* sits the *Ferrel cell*, whereby part of the air driven upward at 60° moves equatorward until it encounters the downwelling of the equatorial Hadley cell. While a similar stack of circulation cells could be generating the banded structure of Jupiter, the scenario is made more complicated by the fact that the planet lacks a solid surface and spins much more rapidly.

There are two basic models that describe how the observed zonal winds develop with depth. The first model describes the weather observed at the top of the atmosphere as *shallow*, which is closely analogous to that on Earth, where the winds are naturally bound by a lower boundary (i.e., the surface). At the giant planets, such a boundary would move at an angular velocity equal to the interior rotation period, and there could exist strong vertical velocity gradients within the shallow weather layer. While this model works well for the terrestrial planets, it has several shortcomings at the giant planets: (a) In order to maintain a banded structure that remains largely invariant over long timescales, energy is required to be pumped into the system. (b) These models predict that the midlatitude circulation cells are the same size as the equatorial cell, which is not the case. (c) They predict strong westward equatorial jets at the gas giants (Jupiter and Saturn), whereas the jets are observed to be eastward.

The second model is the *deep model*, where the observed wind at the top of the troposphere extends deep into the interior. According to the Taylor–Proudman effect (Taylor, 1923), a rapidly rotating fluid sphere will organize into many rotating concentric cylinders that are aligned along the rotational axis (Ingersoll and Pollard, 1982). This is illustrated in Figure 5. In this scenario, the belts and zones at low to midlatitudes are physically connected to their counterparts in the

opposite hemisphere via these cylinders, which would explain the symmetric nature of Jupiter’s banded structure. At higher latitudes, however, the presence of a liquid helium core intersects the cylindrical flow, and so the symmetric banded structure would break down in these regions and create a more stochastic atmosphere. The boundary between the two regimes of connected and disconnected cylinders is known as the *critical latitude*. This simple idea largely agrees with what is observed, particularly on Jupiter. The size of these cylinders, and therefore the resultant banded structures of a planet, are governed by both the size and rotation rate, and smaller planets with a longer rotation rate generate larger cylinders and therefore fewer belts and zones. The deep model predicts that the zonal winds observed at the top of the cloud deck would continue very deep into the atmosphere, which was indeed observed by the Galileo probe down to the 240-atmosphere pressure level (Young, 2003).

4.4 Turbulence and Instabilities

The basic circulation pattern outlined in Section 4.3 provides an understanding of the broadscale movement of the atmosphere. However, superposed on this are smaller-scale movements that depart from the mean flow, known as *eddy motions*. These take the form of *turbulence*, *vortices*, and *waves*, which arise from instabilities produced by gradients in temperature, motion, or pressure. Turbulence is ultimately a consequence of instabilities in the atmosphere, and the *Richardson number* provides a measure of the stability of turbulence; if the number is less than one, the turbulent behavior will persist. There are several instabilities relevant to the atmospheres of the giant planets:

- *Static instability* occurs when a rising parcel cools more quickly than the surrounding atmosphere (i.e., the adiabatic lapse rate), which in turn makes it less buoyant, disrupting the convective flow.
- *Inertial (or dynamic) instability* occurs when the pressure gradient force and the centrifugal forces are not evenly balanced inside a vortex, and the frictional forces can generate heat that drives instabilities.
- *Barotropic instability* happens in a regime where the vertical temperature across a region remains constant along lines of constant pressure (which is the barotropic condition). Here, instabilities can arise from a shear in the horizontal velocity field, which in turn can generate vortices.
- *Baroclinic instability* occurs in conditions where the barotropic condition does not hold (i.e., temperatures do not remain constant along lines of constant pressure). Consequently, instabilities can be generated by changing vertical temperature gradients.
- *Kelvin–Helmholtz instability* is produced when two adjacent regions have different wind speeds, creating a shear between the two.

4.5 Waves

Different types of waves play important roles in the atmospheres of the giant planets. They can alter the temperatures and densities along their path, and they can transfer energy and momentum from one atmospheric layer to another or within an atmospheric layer. Waves are simply characterized by their amplitude, wavelength, and phase, which can evolve over time. At the giant planets, there are three types of waves that are particularly important:

Gravity waves (not to be confused with the astrophysical “gravitational waves”) are generated at the boundaries of atmospheric parcels with different motion (e.g., in turbulent regions). Gravity

waves, generated in the troposphere, are divided into two categories: high-frequency *internal* gravity waves and low-frequency *inertia* gravity waves. These can propagate both vertically and horizontally. When they travel upward in altitude, they can break in the stratosphere and upper atmosphere, coupling these different regions. In the stratosphere, these waves provide the primary energy source for eddy mixing (Strobel et al., 1985). These waves can also reach the upper atmosphere, and fine-scale ionospheric disturbances observed above the GRS on Jupiter were linked to the deposition of multiple gravity waves (Melin et al., 2024).

Rossby waves have long wavelengths and large amplitudes, undulating horizontally along lines of constant longitude in rotating systems. They are a type of inertial wave and arise from the conservation of potential vorticity. On Earth, Rossby waves are believed to be responsible for the quasibiennial oscillation, and on Jupiter, a similar phenomenon is observed—the quasiquadrennial oscillation, which manifests as a temperature perturbation in the stratosphere that slowly moves down in altitude with a period of about 4 years (Leovy et al., 1991).

The Kelvin–Helmholtz instability outlined in Section 4.4 is generated at the interface between two different flow regimes. If the shear flow is large enough, *Kelvin–Helmholtz waves* form along the boundary, and they provide a mechanism for transferring energy and momentum between the two regions.

4.6 Lightning

Electrification is the build-up of charge within a parcel of the atmosphere and is a common process. On Earth, clouds contain water in different phases (i.e., liquid, solid, and ice). Light ice crystals are transported upward in altitude in the convective core of a cloud, while larger and heavier soft hail, known as *graupel*, moves downward. Collisions between them transfer electrons to the heavier particles, rendering the top of the cloud positively charged and the bottom negatively charged.

Lightning is the electrostatic discharge between two regions with different electric charges that have undergone electrification. Its physical manifestation is a bright flash caused by electrons tearing through the atmosphere, followed by thunder associated with the shock wave produced by the movement of the electrons, producing compressional waves in the atmosphere. Lightning has been directly observed on Jupiter (Cook et al., 1979) and Saturn (Warwick et al., 1981) and has been indirectly detected on Uranus (Zarka and Pedersen, 1986) and Neptune (Gurnett et al., 1990). This process is believed to be similar to what is seen on Earth, generated in the low-altitude water clouds. Instead of the terrestrial graupel, the term *mushball* has been used, where soft hail is enriched with ammonia (Guillot et al., 2020b).

4.7 Disequilibrium Species

For a particular molecular species, there is a temperature and pressure at which it can exist in chemical equilibrium, where the molecular abundance remains constant and the production and destruction chemical reactions are equally balanced. Molecules can also exist in a disequilibrium state, whereby the destruction or production processes will dominate over the other, leading to reduced or increased abundances relative to their equilibrium state. Molecules are transported vertically from altitudes at which they are in equilibrium to a state of disequilibrium by the strong overturning of the dynamic atmosphere. Therefore, observing species in a state of disequilibrium will provide essential information about the dynamics and circulation of the atmosphere. At the giant planets, important disequilibrium species are nitrogen, carbon, germane, arsine, ammonia, and phosphine, as well as different spin states of atoms in the hydrogen molecule.

The first observation of how a disequilibrium species is distributed at great depth on Jupiter came

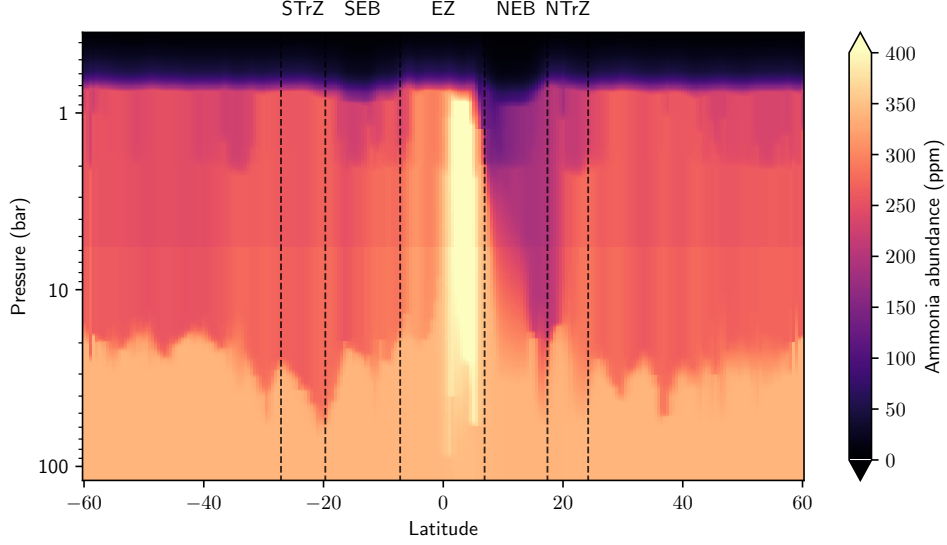


Figure 6: The deep vertical ammonia abundance as measured by the Juno Microwave Radiometer (MWR). *Source:* Adapted from [Moeckel et al. \(2023\)](#).

from the Juno MWR, which observed the deep abundance of ammonia ([Li et al., 2017](#); [Moeckel et al., 2023](#)), as shown in Figure 6. It shows significant variations in the abundance at high pressures (>10 bar) and a significant enhancement throughout the entire atmospheric column at the equator, with a depletion just north of this enhancement. This curious distribution may be related to the presence of thunderstorms, where the formation of mushballs efficiently removes ammonia from that column of atmosphere. The absence of thunderstorms at the equator then allows an enrichment in the Equatorial Zone ([Guillot et al., 2020a](#)).

5 Gas Giants

Jupiter and Saturn are classed as gas giants because their bulk composition consists mainly of hydrogen and helium, and this composition makes them different from the ice giants, Uranus and Neptune.

5.1 Jupiter

The visual appearance of Jupiter is dominated by the bright *zones* and dark *belts*, which appear in pairs across the planetary disk. The zones are regions in which convective upwelling occurs, bringing material from the deep atmosphere, such as condensable and disequilibrium species, and the subsequent downwelling occurs in the belts. As a result of this convection, the zones are hotter than the belts, since deeper tropospheric altitudes experience lower temperatures. There is a strong east–west (i.e., zonal) wind shear between the belts and the zones, creating instabilities (see Section 4.4) that can produce vortices or cyclonic storms. The zones closest to the Equatorial Zone (EZ) are called the North and South Equatorial Belts (NEB and SEB), followed by the North and South Tropical Zones (NTrZ and STrZ). Apart from the turbulent behavior at the boundaries of these regions, they appear stable on timescales of decades. However, they routinely undergo dramatic changes, some of which are cyclic (e.g., [Antuñano et al., 2018](#)).

The belt-zone structure is broadly compatible with the circulation patterns outlined in Section 4.3, with upwelling at the EZ and downwelling in the Equatorial Belts, forming a Hadley cell, followed by belts and zones produced by the deep Taylor–Proudman circulation. However,

observations by the Juno microwave radiometer, which penetrates deep into Jupiter’s troposphere, have hinted that this simple single-cell behavior may be more complex. Instead of one cell, Jupiter may have stacked circulation cells, whereby at depth, the EZ experiences downwelling (Fletcher et al., 2021; Ingersoll et al., 2000). The boundary at which the cylinders switch direction has been termed the *jovicline*. Toward the poles, above latitudes of $\sim 70^\circ$, this patterned behavior is replaced with a more chaotic, asymmetric atmosphere, and stable circumpolar cyclones have been detected by the Juno spacecraft in both the north and the south (Adriani et al., 2018).

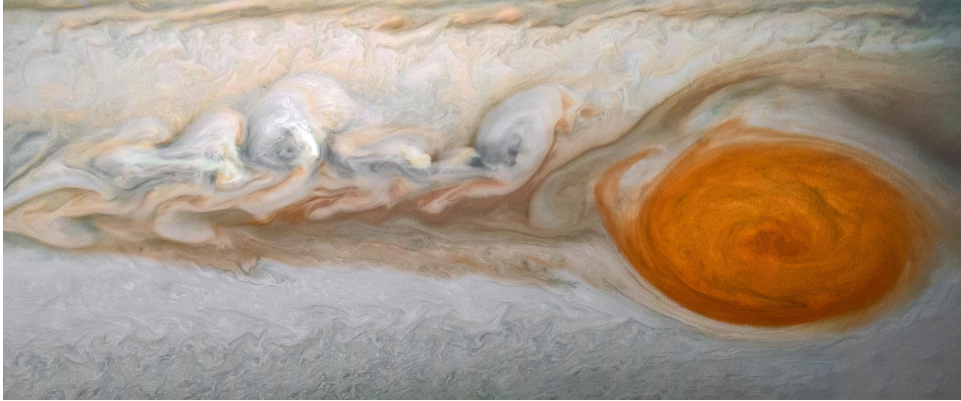


Figure 7: A JunoCam observation of Jupiter’s Great Red Spot (GRS) from September 7, 2023. *Source:* NASA/JPL-Caltech/SwRI/MSSS, image processing by Kevin M. Gill, © CC BY.

The most striking feature in the atmosphere of Jupiter is the GRS, as shown in Figure 7. It is the largest and longest-lived vortex in the Solar System. The center of the storm shows large amounts of aerosol reflectance and relatively modest wind speeds. The bulk of the motion is confined to a ring surrounding the storm that prevents any mixing with the surrounding regions (Fletcher et al., 2010). The storm is relatively shallow, extending only about 500 km in altitude (Parisi et al., 2021), which means that its vertical extent is only 0.5% of its horizontal extent and that it is disconnected from the deep zonal flows that surround it. The distinct reddish color of the storm is thought to be due to some hitherto unknown chromophore, likely a photochemical product of ammonia and acetylene (Baines et al., 2019).

5.2 Saturn

The international Cassini mission to Saturn spent 13 years orbiting the planet, completing 294 orbits. This hugely successful mission made many significant discoveries, including cryovolcanic geysers on the moon Enceladus (Dougherty et al., 2006), methane lakes on Titan (Stofan et al., 2007), and the fact that measurements of the rotation rate appear to yield different results in the northern and southern hemispheres (Gurnett et al., 2009). Additionally, Cassini carried the European Huygens probe, which became the first probe to land on a moon in the outer Solar System (Lebreton et al., 2009).

Saturn has an axial tilt of $\sim 27^\circ$, which produces strong seasonal behavior. The changing solar illumination alters the stratospheric photochemistry, and at the northern solstice, increased absorption of sunlight by methane drives increased temperatures in the upper troposphere and lower stratosphere (Fletcher et al., 2018).

The tropospheric zonal wind speeds at Saturn show a similar intricate structure to that of Jupiter (Figure 4), also associated with broadscale belt and zone structures (Figure 8). Saturn exhibits much larger velocities than Jupiter, especially at the equator, where winds can reach up to 400 m s^{-1} , and these are likely linked to the deep motion of the atmosphere in the form of

Taylor–Proudman-type cylinders. Using radio observations from the ground, the stratospheric wind speeds can also be measured, showing that the equatorial jet extends up to the 10 μ bar level (Benmahi et al., 2022).

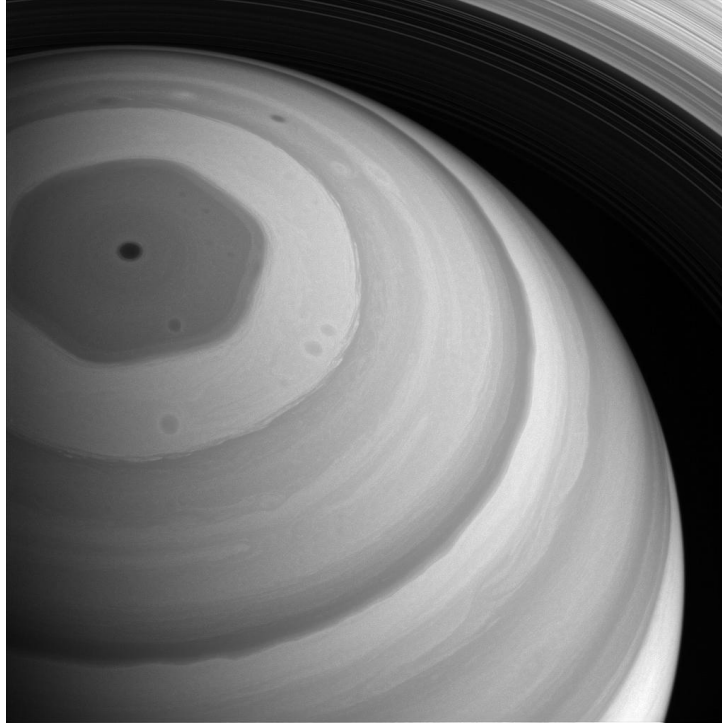


Figure 8: The hexagon in Saturn’s northern hemisphere obtained by Cassini at 728 nm. *Source:* NASA/JPL-Caltech/Space Science Institute.

One of the more remarkable features of Saturn’s troposphere is the presence of a persistent polar hexagon in the northern hemisphere (Godfrey, 1988), as shown in Figure 8. This six-sided feature is very stable and remains fixed in longitude (Godfrey, 1990) and is believed to be formed by a Rossby wave generated by instabilities in the nearby zonal jet at 78°N (Allison et al., 1990). The Cassini spacecraft acquired remarkable views of this feature, and midinfrared observations show that it extends well up into the stratosphere, altering the temperature structure (Fletcher et al., 2018).

A semiregular occurrence at Saturn is the emergence of an intense convective bright storm in the northern spring (McKim, 2011) that eventually extends and envelops the northern hemisphere. The instability that generates the intense moist convection of these events is likely linked to the fact that the stratospheric temperature is strongly driven by the seasonal illumination, but the preference for the northern hemisphere remains unknown (Sanchez-Lavega et al., 2018).

6 Ice Giants

The ice giants, Uranus and Neptune, are smaller and denser than the gas giants (see Table 1). While the outer envelopes of these planets are dominated by hydrogen and helium, they have a higher proportion of heavier elements at depth. The term *ice giants* derives from the fact that, at depth, they may well be dominated by “icy” materials, such as water and methane, though in a hot and fluid state (Hubbard et al., 1995; Podolak et al., 1991). However, considerations of the distribution of carbon monoxide and its sources (i.e., external or internal) have led to the suggestion that the interiors may be more dominated by rock than by ices, and perhaps the term *rock giant* would be more appropriate (Teanby et al., 2020).

The atmospheres of these planets are very cold (see Figure 2), which means that the thermal emission features from their atmospheric constituents emit weakly, and their distance from the Sun also renders reflected light very weak, with both effects making them challenging to observe. Uranus and Neptune have only been visited by a single spacecraft—both were visited by the Voyager 2 spacecraft in 1986 and 1989, respectively. Hence, scientific understanding of these two planets is much more limited than that of Jupiter and Saturn. Thus, it is certain that a new interplanetary spacecraft mission to either of these planets would provide invaluable information about these worlds.

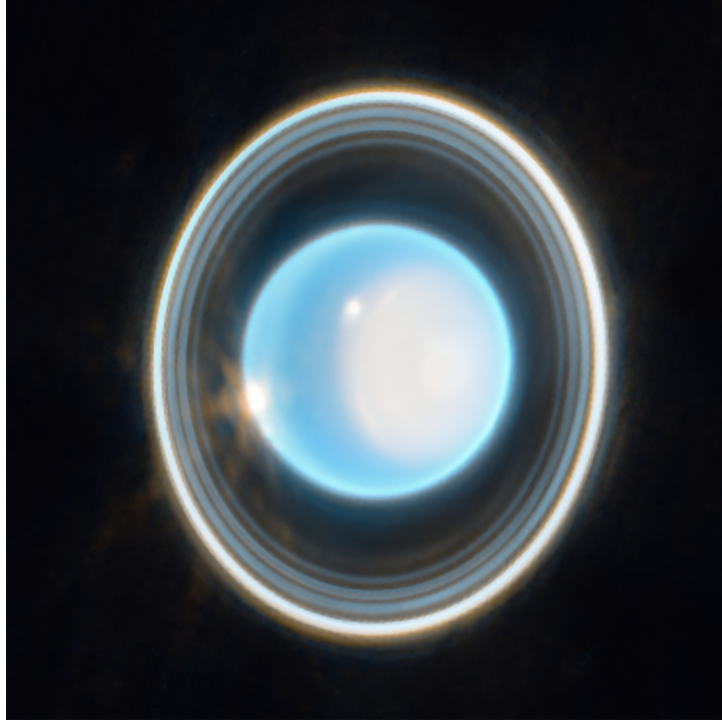


Figure 9: Uranus imaged by NIRCam on the James Webb Space Telescope (JWST) in the infrared. *Source:* NASA, ESA, CSA, STScI.

6.1 Uranus

Uranus is unique in many ways. It effectively rotates “on its side,” generating extreme seasons, during which the northern pole is sunlit all the time at northern solstice (Figure 9). The planet also has very little internal heat (Pearl et al., 1990). Models have suggested that the rotational geometry and lack of internal heat could be linked: a large collision in the early Solar System could have knocked the planet on its side and at the same time released most of its stored internal heat (Ida et al., 2020). The strange nature of Uranus’s orbital geometry makes it an interesting laboratory for understanding planetary atmospheres.

The lack of internal heat should, in principle, produce a very sluggish atmosphere, with the lack of energy available at the bottom of the troposphere severely limiting convection. However, there are several indications that despite the lack of an internal heat source, significant dynamics are present on the planet. First, with limited internal heat, solar forcing may be expected to dominate as a heat source, which would produce a warmer atmosphere at the subsolar point and a cooler atmosphere toward the limb. However, Voyager 2 measured very little variability in the temperature at the top of the troposphere (Flasar et al., 1987; Hanel et al., 1986). Second, just like on Jupiter, condensable species on Uranus, such as methane and hydrogen sulfide, are important tracers of tropospheric circulation. These are observed to have strong gradients

indicative of equator-to-pole circulation that appears independent of solar irradiation (Moses et al., 2020). Third, the extreme and long seasons on Uranus should generate strong seasonal behavior if sunlight dominates as an energy source. This is not observed, however, and the structure of the temperatures in the upper troposphere and lower stratosphere has remained largely constant over the 40 years since the Voyager 2 flyby (Orton et al., 2015; Roman et al., 2020).

The zonal wind speeds of Uranus in Figure 4 show retrograde winds at the equator and prograde winds at midlatitudes. Analysis of the higher-order moments of the gravity field suggests that these winds are relatively shallow, extending 1,000 km in altitude (Kaspi et al., 2013). In the troposphere, the broadscale circulation is believed to be upwelling at the equator and downwelling at the pole (Conrath et al., 1998), painting a much simpler picture than what is seen on Jupiter and Saturn. However, Uranus does not lack complexity. For example, Uranus is likely to have intricate cloud structures where cold temperatures allow methane to condense to form clouds in the troposphere (Lindal et al., 1987), along with clouds of water, hydrogen sulfide, and ammonia hydrosulfide (Hueso et al., 2020).

In the stratosphere of Uranus, methane photochemistry drives heating, just like on Jupiter. However, the limited internal heat limits the vertical mixing by eddy diffusion, which produces a relatively deep methane homopause (Herbert et al., 1987; Moses et al., 2018), which in turn produces an extended upper atmosphere (Melin, 2020).

6.2 Neptune

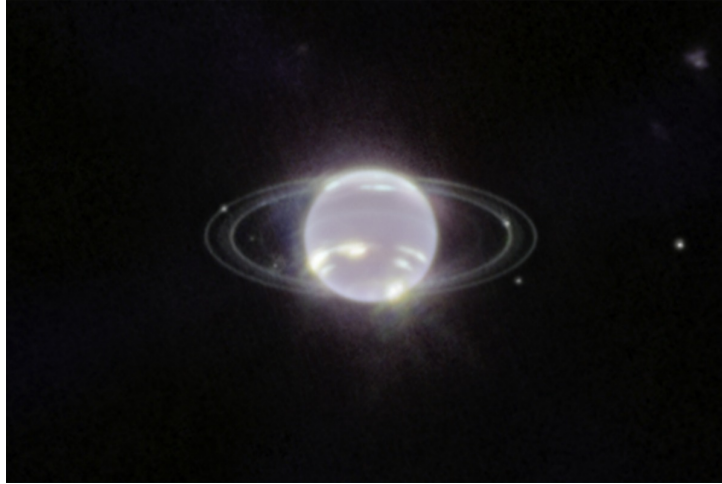


Figure 10: Neptune imaged by NIRC2 on the JWST. *Source:* NASA, ESA, CSA, STScI, image processing by Joseph DePasquale (STScI) and Naomi Rowe-Gurney (NASA-GSFC).

The visual appearance of Neptune is dominated by bright clouds that disappear within days of appearing (Figure 10). The rapidly changing nature of these outbreaks is likely primarily driven by the large internal heat flux of the planet, which drives strong moist convection in the lower atmosphere. A similar complex set of cloud decks as is expected on Uranus is likely present on Neptune.

The tropospheric zonal winds of Neptune are the fastest observed among the giant planets (Figure 4). The equator is strongly retrograde with wind speeds of up to 400 m s^{-1} , with weaker prograde winds of $\sim 250 \text{ m s}^{-1}$ at higher latitudes. The planet is thought to have a similar tropospheric convection pattern to that of Uranus, with upwelling at the equator and downwelling at the poles. Using radio observations, the stratospheric winds can be directly measured (Carrión-González et al., 2023) and decay significantly with altitude, in line with

what is derived by applying the thermal wind equation to the tropospheric winds (Fletcher et al., 2014). As the winds decay with altitude, a drag force is inferred, which may be in the form of breaking gravity waves. Ultimately, the mechanisms that drive these extreme and largely unchanging winds remain unknown.

While the lower stratospheric temperature of Uranus seems to change very little with time, the stratosphere of Neptune can change on timescales much shorter than the long seasons (Roman et al., 2022). These changes may in part be related to the 11-year solar cycle, which modulates the solar ultraviolet emissions, which in turn regulate stratospheric photochemistry. There is also a solar cycle dependence on the emergence of bright clouds (Chavez et al., 2023), which may indicate that even at a great distance from the Sun, it still governs fundamental aspects of Neptune’s atmosphere.

The large internal heat flux of Neptune drives vigorous eddy diffusion in the stratosphere, which, in turn, has the effect of producing a very high methane homopause (Moses et al., 2018), which in turn produces a very compact thermosphere and ionosphere, in stark contrast to Uranus, whose methane homopause and distribution of hydrocarbon daughter products are very shallow (Orton et al., 2014).

7 Tools of the Trade

Most understanding of the atmospheres of the giant planets is derived from remote sensing observations, where the planets are observed at great distances. The one exception to this is the Galileo Probe, which provided in situ measurements and is discussed later in this section.

The atmospheres of these planets can be explored both with imaging and spectroscopy targeting different wavelength regions. Since the observed radiances from molecular bands are dependent on temperature, separate observations are often obtained at wavelength regions from which the temperature can be determined. For example, to investigate the abundances of the methane photochemical products acetylene and ethane in the stratosphere of Jupiter, which can be observed at $13.4\ \mu\text{m}$ and $12.2\ \mu\text{m}$, respectively, the temperature at these altitudes can be constrained by observing the methane emission at $8.0\ \mu\text{m}$ (e.g., Melin et al., 2018). The midinfrared contains a plethora of emission and absorption features from giant planet atmospheres and is therefore commonly used, but other wavelength bands also contain important information, from the ultraviolet to the microwave.

7.1 Ground-Based Telescopes

Telescopes on the ground provide important constraints on the atmospheres of the giant planets. However, they are limited by Earth’s atmosphere, which effectively sits between the telescope and the planet in question, in two basic ways. First, the turbulent motion of the telluric atmosphere introduces a blurring of the observations, known as *seeing*. This can be corrected by using *adaptive optics*, available at some telescopes, which correct for this by deforming the primary or secondary mirror at a very high rate. Second, the molecules in Earth’s atmosphere absorb light at certain wavelengths, making certain parts of the electromagnetic spectrum inaccessible from the ground. For example, water, carbon monoxide, and methane absorb across broad bands in the near and midinfrared. Further complexity is added if one studies these species at the giant planets: the planets must be observed at an appropriate time when the relative motion between the Earth and the planet effectively Doppler shifts these lines away from the molecular features in Earth’s atmosphere.

Most of the world’s premier observatories are found at high altitude, above Earth’s tropospheric inversion layer. For example, Mauna Kea in Hawaii is an ideal site for infrared astronomy

because of its dry and stable atmosphere, sitting 4,100 m above sea level.

7.2 Space Telescopes

By placing telescopes in space, the limitations introduced by observing through Earth’s atmosphere can be eliminated. The first operational space telescope was the Orbiting Astronomical Observatory-2, launched in 1968, which operated until 1973. Since then, there have been a number of space telescopes, but arguably the most important is the Hubble Space Telescope, launched in 1990. Long-term programs like the Outer Planet Atmospheres Legacy program have provided invaluable monitoring of the four giant planets since 2015.

The James Webb Space Telescope (JWST) was launched on Christmas Day 2021 and is the largest and most complex infrared observatory ever constructed. It orbits far away from Earth (unlike the Hubble Space Telescope) and was designed to sense the first stars and galaxies formed in the very early universe. Therefore, it has four extremely sensitive instruments, covering a wavelength range between 0.6 and $28.5\,\mu\text{m}$ for both imaging and spectroscopy. All four of the giant planets have been observed, and the early results have revealed Jupiter’s Great Red Spot in great detail (Harkett et al., 2024), narrow jets in Jupiter’s equatorial stratosphere (Hueso et al., 2023), complex patterns in Jupiter’s ionosphere (Melin et al., 2024), and seasonal changes in Saturn’s polar atmosphere (Fletcher et al., 2023). This is only the advent of exploring the giant planets with JWST, and as more data are gathered, especially at the ice giants where the molecular features are very weak, scientists are poised to gain a much deeper understanding of these systems.

7.3 Spacecraft Missions

Even with the best telescopes in the world, the finer details of atmospheric structure and dynamics can only be resolved by spacecraft flying close to the planet. The first close-up views of Jupiter in the visible and infrared were provided by Pioneer 10 in 1973, followed by Pioneer 11 in 1974, with the latter reaching Saturn in 1979. These missions were the preamble to the Voyager 1 and 2 Grand Tour, with the Voyager 2 spacecraft going on to visit all four giant planets, thanks to a fortuitous planetary alignment that only occurs once every 175 years. Voyager 1 flew by Jupiter in 1979 and Saturn in 1980 and included a flyby of Titan, Saturn’s largest moon. The orbital constraints required for the Titan flyby took the probe out of the orbital plane. Voyager 2 went on to visit both Uranus in 1986 and Neptune in 1989. These bold missions laid the foundation for the modern-day exploration of the giant planets, and their importance cannot be overstated. Amazingly, both Voyager 1 and 2 are still operational, exploring the heliospheric boundary.

The Galileo mission to Jupiter launched aboard Space Shuttle Atlantis in 1989, following a five-year delay caused by the Challenger disaster. The mission was severely hampered by the fact that the high-gain antenna did not deploy properly, probably related to the degradation of lubricants during the extended period that the spacecraft sat in storage. Nonetheless, the spacecraft delivered the Galileo Entry Probe upon arrival in 1995 and deorbited in 2003. Despite the limited data rates that Galileo could transmit back to Earth, the mission achieved most of its science objectives: besides being the first to deliver a direct probe of an outer-planet atmosphere, it was the first to make spectral images of Jupiter in the near-infrared.

NASA’s Juno mission, launched in 2011, entered orbit around Jupiter in 2016. The highly inclined orbits pass above the poles and skim the top of the equatorial atmosphere during each pass. The prime mission was highly targeted to study the auroral process and the magnetic and gravity fields of Jupiter. The mission was, as of 2025, in its extended phase, which continues its close flybys of Jupiter, as well as flybys of Jupiter’s moons.

The very successful Cassini mission to Saturn, which also flew by Jupiter in late 2000, set a gold standard for international collaboration. These large flagship missions are very expensive and complex, and by involving expertise and funding from multiple space agencies, the considerable challenges of these projects can be solved. This is clearly good for the scientific outcome of these missions, but it also brings international communities together.

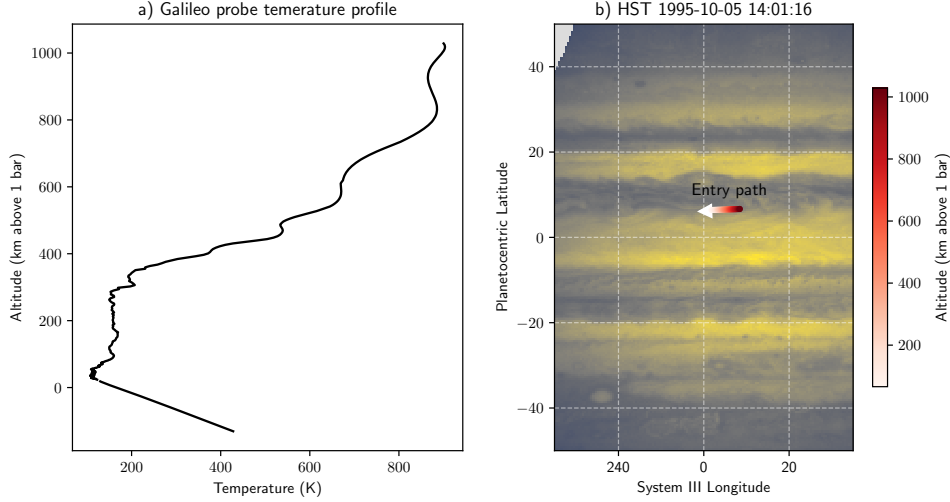


Figure 11: (a) The vertical temperature profile as measured by the Galileo probe (Seiff et al., 1996) on December 7, 1995. (b) A Hubble Space Telescope Wide Field Camera 3 image taken on October 5, 1995, using the F410M filter. The entry path of the probe while traversing the upper atmosphere is shown, where the color indicates the altitude of the spacecraft measurement.

7.4 Entry Probes

There are distinct advantages to sending a probe into an atmosphere to measure the composition, temperature, and pressure as it descends. First, it provides a “ground truth” for remote sensing observations. Second, there are certain important species that cannot easily be measured via remote sensing at high atmospheric pressures. In particular, the noble gases (helium, neon, argon, krypton, and xenon) provide critical constraints on the formation and evolution of these planets.

The only in situ observations of a giant planet atmosphere came from the Galileo probe, which entered Jupiter’s atmosphere on December 7, 1995, and descended to pressures of 24 bar before the signal was lost. It carried a suite of instruments that measured the vertical composition and temperature structures. Figure 11 shows the measured vertical temperature profile along with a reference HST WFC3 image obtained about a month before the probe descent, showing the path the probe took through the atmosphere. The temperature measurements are from the Atmosphere Structure Instrument and were reported by Seiff et al. (1996). The probe traversed several degrees of longitude toward the east during the descent, skirting the North Equatorial Belt, a region where downwelling occurs. The probe measured a very dry atmosphere, with very little water, which was ultimately attributed to the probe entering a dry “hot spot” of the atmosphere (Orton et al., 1998; Wong et al., 2008). This illustrates the potential problem with an entry probe—a single-point measurement may not be representative of the entire atmosphere.

7.5 Radiative Transfer Calculations

The various types of observations of the atmospheres of the giant planets are often interpreted using *radiative transfer* modeling. These models calculate the way light propagates through an

atmosphere, subject to solar illumination, deep thermal radiation, and absorption and scattering by the atmospheric constituents as well as clouds, aerosols, and hazes. They require inputs such as vertical profiles of temperature and abundance and the optical properties of the clouds, aerosols, and hazes.

In general, radiative transfer can be applied in two ways. First, a *forward model* will take the vertical profiles of abundances, temperature, and any cloud and aerosol structure to produce a spectrum as it would appear at the top of the atmosphere. This can be thought of as a prediction of what a particular instrument would observe. The second way is a *retrieval*, whereby the opposite takes place, and based on an observed spectrum, the calculations will provide the composition, temperature, clouds, and aerosol structures that best fit the observed data. This is a powerful technique that allows constraints on the vertical profiles.

7.6 Future Prospects

Both the ESA JUICE mission and the NASA Europa Clipper mission are on their way to Jupiter, which will provide up-close views of Jupiter’s atmosphere in the 2030s. Ultimately, JUICE will go into orbit around Ganymede, and Europa Clipper will go into orbit around Europa to explore these enigmatic moons.

The last visit to Uranus and Neptune was by Voyager 2 in 1986 and 1989, respectively. There is growing consensus in the planetary science community that a new, Cassini-style flagship mission to either of these planets would provide significant scientific value, and a Uranus mission was ranked the highest in the National Academy of Sciences Decadal Strategy for Planetary Science and Astrobiology 2023–2032 ([National Academies of Sciences, Engineering, and Medicine, 2023](#)). In order to perform a gravity assist on Jupiter, a launch date by 2031 would be required, with an estimated arrival in 2044. To operate a spacecraft over these long durations, far away from the Sun, a radioisotope thermoelectric generator is required to provide power and heating for the subsystems. While there is a plutonium shortage, other alternatives are being explored at ESA using americium (Am). The Uranus Orbiter and Probe mission concept ([Simon et al., 2021](#)) outlines a payload that includes a descent probe to be dropped into the atmosphere, providing a ground truth for future measurements, in a similar way to the Galileo probe on Jupiter.

Lastly, there are a number of 30-m-class telescopes under construction or in the planning phase. Generally, these offer limited fields of view but provide high sensitivity and so will be well suited to observing the ice giants, which are often challenging to observe with smaller telescopes. One example of this new class of telescope is the Extremely Large Telescope in Chile, which is a 39-m-diameter telescope that can achieve diffraction-limited spatial resolution.

8 Conclusion

The thermal structure, composition, and behavior of the atmospheres of the giant planets have been outlined in broad strokes. While similarities exist, especially within the subsets of gas giants and ice giants, significant differences are present. These differences mean that the four planets exhibit different atmospheres, and each atmosphere provides a unique laboratory in which to understand how these systems behave.

Broadly speaking, the atmospheres of the giant planets are convectively driven at depth by the latent internal heat, and as the atmosphere gets more rarefied and less opaque with increasing altitudes, radiative processes become more important, including solar-driven photochemistry in the stratosphere and upper atmosphere. Instabilities, vortices, and waves are all important for understanding the small-scale behavior, the generation of convective outbreaks, and the transfer of energy and momentum within these atmospheres.

A great number of fundamental questions about the atmospheres of the giant planets remain, and outlined here is a (subjective) list of some of the more pressing ones:

- What drives the fast zonal winds? How can they remain stable over time? How (and why) do they decay with altitude? How deep do they penetrate? Why does Neptune have strong retrograde winds, while Jupiter is dominated by prograde winds?
- How are the different atmospheric layers coupled on the giant planets? How do energy and momentum move within and between different layers?
- Why does Uranus have so little internal heat?
- What are the abundances of noble gases? They provide important constraints on the formation process of the Solar System, and so how do these abundances compare with different formation scenarios?
- Where do the giant planets sit on the spectrum of giant extrasolar planets? Are they “typical” of this larger sample?

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