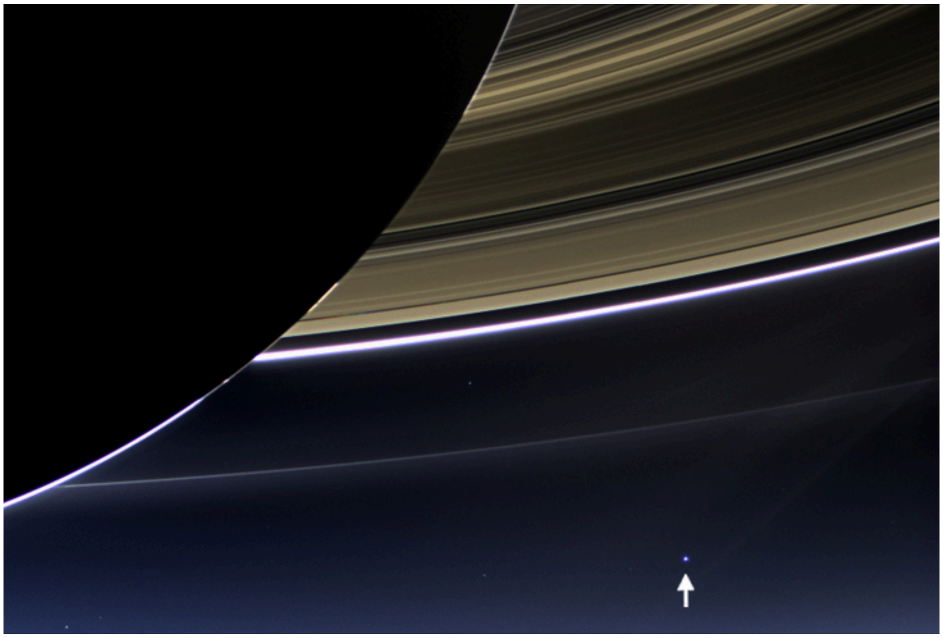

**Figure 11.4 Earth as Seen from Saturn.** This popular Cassini image shows Earth as a tiny dot (marked with an arrow) seen below Saturn's rings. It was taken in July 2013, when Saturn was 1.4 billion kilometers from Earth. (credit: modification of work by NASA/JPL-Caltech/Space Science Institute)

# 11.2 THE GIANT PLANETS

## Learning Objectives

By the end of this section, you will be able to:

- Describe the basic physical characteristics, general appearance, and rotation of the giant planets
- Describe the composition and structure of Jupiter, Saturn, Uranus, and Neptune
- Compare and contrast the internal heat sources of the giant planets
- Describe the discovery and characteristics of the giant planets' magnetic fields

Let us now examine the four giant (or *jovian*) planets in more detail. Our approach is not just to catalog their characteristics, but to compare them with each other, noting their similarities and differences and attempting to relate their properties to their differing masses and distances from the Sun.

## Basic Characteristics

The giant planets are very far from the Sun. Jupiter is more than five times farther from the Sun than Earth's distance (5 AU), and takes just under 12 years to circle the Sun. Saturn is about twice as far away as Jupiter (almost 10 AU) and takes nearly 30 years to complete one orbit. Uranus orbits at 19 AU with a period of 84 years, while Neptune, at 30 AU, requires 165 years for each circuit of the Sun. These long timescales make it difficult for us short-lived humans to study seasonal change on the outer planets.

Jupiter and Saturn have many similarities in composition and internal structure, although Jupiter is nearly four times more massive. Uranus and Neptune are smaller and differ in composition and internal structure from their large siblings. Some of the main properties of these four planets are summarized in Table 11.3.

**Basic Properties of the Jovian Planets**

| Planet | Distance (AU) | Period (years) | Diameter (km) | Mass (Earth = 1) | Density ($g/cm^3$) | Rotation (hours) |
|---|---|---|---|---|---|---|
| Jupiter | 5.2 | 11.9 | 142,800 | 318 | 1.3 | 9.9 |
| Saturn | 9.5 | 29.5 | 120,540 | 95 | 0.7 | 10.7 |
| Uranus | 19.2 | 84.1 | 51,200 | 14 | 1.3 | 17.2 |
| Neptune | 30.0 | 164.8 | 49,500 | 17 | 1.6 | 16.1 |

**Table 11.3**

Jupiter, the giant among giants, has enough mass to make 318 Earths. Its diameter is about 11 times that of Earth (and about one tenth that of the Sun). Jupiter's average density is 1.3 g/cm$^3$, much lower than that of any of the terrestrial planets. (Recall that water has a density of 1 g/cm$^3$.) Jupiter's material is spread out over a volume so large that more than 1400 Earths could fit within it.

Saturn's mass is 95 times that of Earth, and its average density is only 0.7 g/cm$^3$—the lowest of any planet. Since this is less than the density of water, Saturn would be light enough to float.

Uranus and Neptune each have a mass about 15 times that of Earth and, hence, are only 5% as massive as Jupiter. Their densities of 1.3 g/cm$^3$ and 1.6 g/cm$^3$, respectively, are much higher than that of Saturn. This is one piece of evidence that tells us that their composition must differ fundamentally from the gas giants. When astronomers began to discover other planetary systems (exoplanets), we found that planets the size of Uranus and Neptune are common, and that there are even more exoplanets intermediate in size between Earth and these ice giants, a type of planet not found in our solar system.

## Appearance and Rotation

When we look at the planets, we see only their atmospheres, composed primarily of hydrogen and helium gas (see **Figure 11.1**). The uppermost clouds of Jupiter and Saturn, the part we see when looking down at these planets from above, are composed of ammonia crystals. On Neptune, the upper clouds are made of methane. On Uranus, we see no obvious cloud layer at all, but only a deep and featureless haze.

Seen through a telescope, Jupiter is a colorful and dynamic planet. Distinct details in its cloud patterns allow us to determine the rotation rate of its atmosphere at the cloud level, although such atmosphere rotation may have little to do with the spin of the underlying planet. Much more fundamental is the rotation of the mantle and core; these can be determined by periodic variations in radio waves coming from Jupiter, which are controlled by its magnetic field. Since the magnetic field (which we will discuss below) originates deep inside the planet, it shares the rotation of the interior. The rotation period we measure in this way is 9 hours 56 minutes, which gives Jupiter the shortest "day" of any planet. In the same way, we can measure that the underlying rotation period of Saturn is 10 hours 40 minutes. Uranus and Neptune have slightly longer rotation periods of about 17 hours, also determined from the rotation of their magnetic fields.

## LINK TO LEARNING

A brief video made from Hubble Space Telescope photos shows **the rotation of Jupiter (https://openstax.org/l/30HSTJupRot)** with its many atmospheric features.

Remember that Earth and Mars have seasons because their spin axes, instead of “standing up straight,” are tilted relative to the orbital plane of the solar system. This means that as Earth revolves around the Sun, sometimes one hemisphere and sometimes the other “leans into” the Sun.

What are the seasons like for the giant planets? The spin axis of Jupiter is tilted by only 3°, so there are no seasons to speak of. Saturn, however, does have seasons, since its spin axis is inclined at 27° to the perpendicular to its orbit. Neptune has about the same tilt as Saturn (29°); therefore, it experiences similar seasons (only more slowly). The strangest seasons of all are on Uranus, which has a spin axis tilted by 98° with respect to the north direction. Practically speaking, we can say that Uranus orbits on its side, and its ring and moon system follow along, orbiting about Uranus’ equator (**Figure 11.5**).

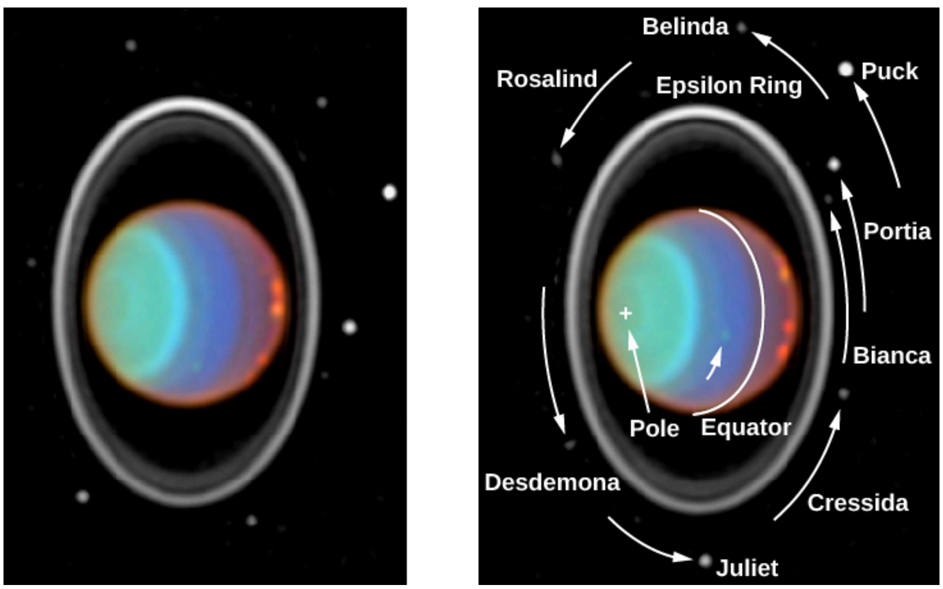


**Figure 11.5 Infrared Image of Uranus.** The infrared camera on the Hubble Space Telescope took these false-color images of the planet Uranus, its ring system, and moons in 1997. The south pole of the planet (marked with a “+” on the right image) faces the Sun; its green color shows a strong local haze. The two images were taken 90 minutes apart, and during that time the five reddish clouds can be seen to rotate around the parallel to the equator. The rings (which are very faint in the visible light, but prominent in infrared) and eight moons can be seen around the equator. This was the “bull’s eye” arrangement that Voyager saw as it approached Uranus in 1986. (credit: modification of work by Erich Karkoschka (University of Arizona), and NASA/ESA)

We don’t know what caused Uranus to be tipped over like this, but one possibility is a collision with a large planetary body when our system was first forming. Whatever the cause, this unusual tilt creates dramatic seasons. When Voyager 2 arrived at Uranus, its south pole was facing directly into the Sun. The southern hemisphere was experiencing a 21-year sunlit summer, while during that same period the northern hemisphere was plunged into darkness. For the next 21-year season, the Sun shines on Uranus’ equator, and both hemispheres go through cycles of light and dark as the planet rotates (**Figure 11.6**). Then there are 21 years of an illuminated northern hemisphere and a dark southern hemisphere. After that the pattern of alternating day and night repeats.

Just as on Earth, the seasons are even more extreme at the poles. If you were to install a floating platform at the south pole of Uranus, for example, it would experience 42 years of light and 42 years of darkness. Any future astronauts crazy enough to set up camp there could spend most of their lives without ever seeing the Sun.

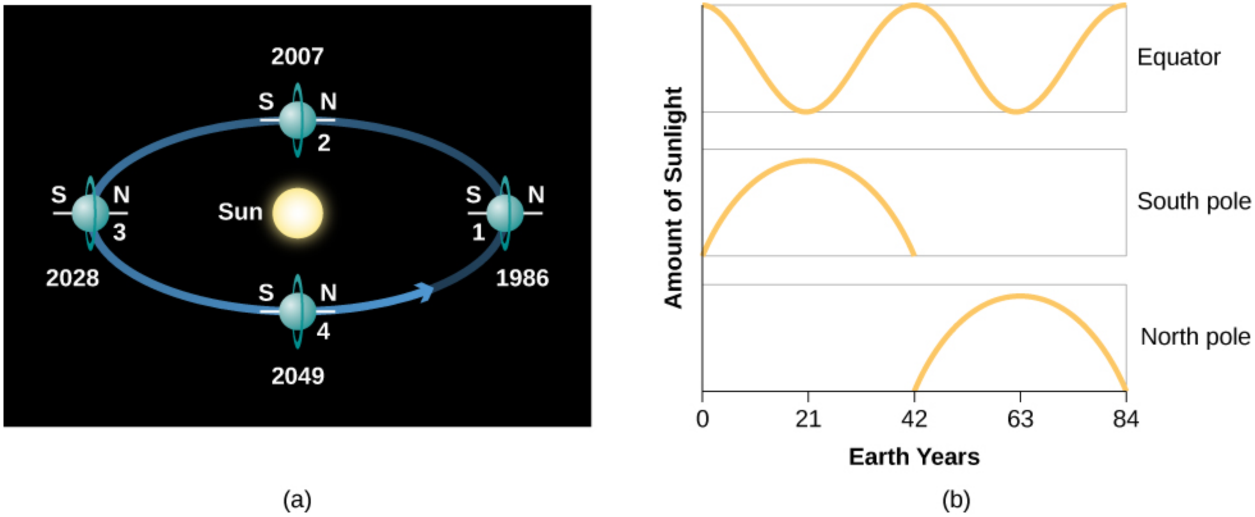


**Figure 11.6 Strange Seasons on Uranus.** (a) This diagram shows the orbit of Uranus as seen from above. At the time Voyager 2 arrived (position 1), the South Pole was facing the Sun. As we move counterclockwise in the diagram, we see the planet 21 years later at each step. (b) This graph compares the amount of sunlight seen at the poles and the equator of Uranus over the course of its 84-year revolution around the Sun.

## Composition and Structure

Although we cannot see into these planets, astronomers are confident that the interiors of Jupiter and Saturn are composed primarily of hydrogen and helium. Of course, these gases have been measured only in their atmosphere, but calculations first carried out more than 50 years ago showed that these two light gases are the only possible materials out of which a planet with the observed masses and densities of Jupiter and Saturn could be constructed.

The deep internal structures of these two planets are difficult to predict. This is mainly because these planets are so big that the hydrogen and helium in their centers become tremendously compressed and behave in ways that these gases can never behave on Earth. The best theoretical models we have of Jupiter's structure predict a central pressure greater than 100 million bars and a central density of about 31 g/cm$^3$. (By contrast, Earth's core has a central pressure of 4 million bars and a central density of 17 g/cm$^3$.)

At the pressures inside the giant planets, familiar materials can take on strange forms. A few thousand kilometers below the visible clouds of Jupiter and Saturn, pressures become so great that hydrogen changes from a gaseous to a liquid state. Still deeper, this liquid hydrogen is further compressed and begins to act like a metal, something it never does on Earth. (In a metal, electrons are not firmly attached to their parent nuclei but can wander around. This is why metals are such good conductors of electricity.) On Jupiter, the greater part of the interior is liquid metallic hydrogen.

Because Saturn is less massive, it has only a small volume of metallic hydrogen, but most of its interior is liquid. Uranus and Neptune are too small to reach internal pressures sufficient to liquefy hydrogen. We will return to the discussion of the metallic hydrogen layers when we examine the magnetic fields of the giant planets.

Each of these planets has a core composed of heavier materials, as demonstrated by detailed analyses of their gravitational fields. Presumably these cores are the original rock-and-ice bodies that formed before the capture of gas from the surrounding nebula. The cores exist at pressures of tens of millions of bars. While scientists speak of the giant planet cores being composed of rock and ice, we can be sure that neither rock nor ice assumes any familiar forms at such pressures and temperatures. Remember that what is really meant by "rock" is any material made up primarily of iron, silicon, and oxygen, while the term “ice” in this chapter denotes materials composed primarily of the elements carbon, nitrogen, and oxygen in combination with hydrogen.

**Figure 11.7** illustrates the likely interior structures of the four jovian planets. It appears that all four have similar cores of rock and ice. On Jupiter and Saturn, the cores constitute only a few percent of the total mass, consistent with the initial composition of raw materials shown in **Table 11.1**. However, most of the mass of Uranus and Neptune resides in these cores, demonstrating that the two outer planets were unable to attract massive quantities of hydrogen and helium when they were first forming.

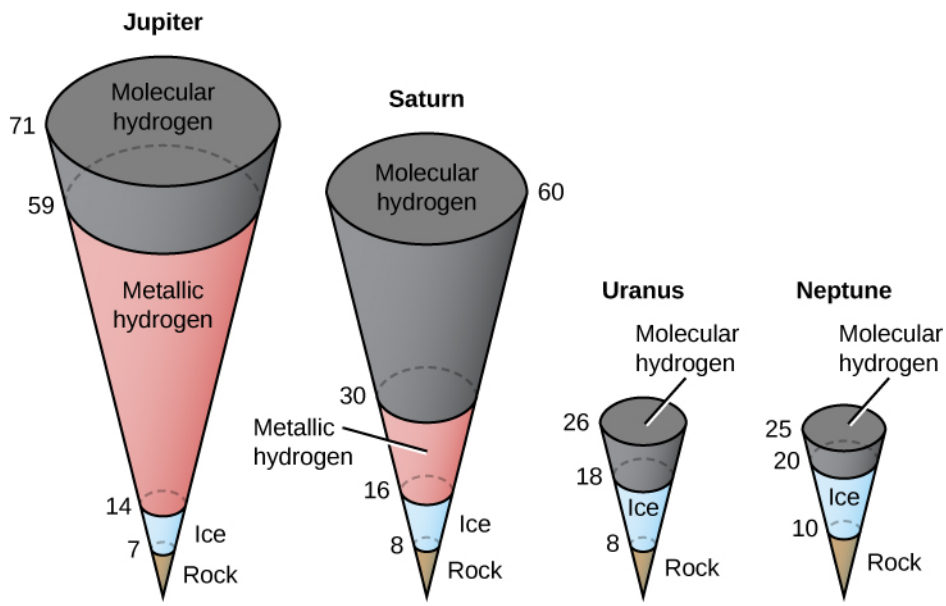


**Figure 11.7 Internal Structures of the Jovian Planets.** Jupiter and Saturn are composed primarily of hydrogen and helium (but hydrogen dominates), but Uranus and Neptune consist in large part of compounds of carbon, nitrogen, and oxygen. (The diagrams are drawn to scale; numbers show radii in thousands of kilometers.)

## Internal Heat Sources

Because of their large sizes, all the giant planets were strongly heated during their formation by the collapse of surrounding material onto their cores. Jupiter, being the largest, was the hottest. Some of this primordial heat can still remain inside such large planets. In addition, it is possible for giant, largely gaseous planets to generate heat after formation by slowly contracting. (With so large a mass, even a minuscule amount of shrinking can generate significant heat.) The effect of these internal energy sources is to raise the temperatures in the interiors and atmospheres of the planets higher than we would expect from the heating effect of the Sun alone.

Jupiter has the largest internal energy source, amounting to $4 \times 10^{17}$ watts; that is, it is heated from inside with energy equivalent to 4 million billion 100-watt lightbulbs. This energy is about the same as the total solar energy absorbed by Jupiter. The atmosphere of Jupiter is therefore something of a cross between a normal planetary atmosphere (like Earth’s), which obtains most of its energy from the Sun, and the atmosphere of a star, which is entirely heated by an internal energy source. Most of the internal energy of Jupiter is primordial heat, left over from the formation of the planet 4.5 billon years ago.

Saturn has an internal energy source about half as large as that of Jupiter, which means (since its mass is only about one quarter as great) that it is producing twice as much energy per kilogram of material as does Jupiter. Since Saturn is expected to have much less primordial heat, there must be another source at work generating most of this $2 \times 10^{17}$ watts of power. This source is the separation of helium from hydrogen in Saturn’s interior. In the liquid hydrogen mantle, the heavier helium forms droplets that sink toward the core, releasing gravitational energy. In effect, Saturn is still differentiating—letting lighter material rise and heavier material fall.

Uranus and Neptune are different. Neptune has a small internal energy source, while Uranus does not emit a measurable amount of internal heat. As a result, these two planets have almost the same atmospheric temperature, in spite of Neptune's greater distance from the Sun. No one knows why these two planets differ in their internal heat, but all this shows how nature can contrive to make each world a little bit different from its neighbors.

## Magnetic Fields

Each of the giant planets has a strong magnetic field, generated by electric currents in its rapidly spinning interior. Associated with the magnetic fields are the planets' *magnetospheres*, which are regions around the planet within which the planet's own magnetic field dominates over the general interplanetary magnetic field. The magnetospheres of these planets are their largest features, extending millions of kilometers into space.

In the late 1950s, astronomers discovered that Jupiter was a source of radio waves that got more intense at longer rather than at shorter wavelengths—just the reverse of what is expected from thermal radiation (radiation caused by the normal vibrations of particles within all matter). Such behavior is typical, however, of the radiation emitted when high-speed electrons are accelerated by a magnetic field. We call this **synchrotron radiation** because it was first observed on Earth in particle accelerators, called synchrotrons. This was our first hint that Jupiter must have a strong magnetic field.

Later observations showed that the radio waves are coming from a region surrounding Jupiter with a diameter several times that of the planet itself (Figure 11.8). The evidence suggested that a vast number of charged atomic particles must be circulating around Jupiter, spiraling around the lines of force of a magnetic field associated with the planet. This is just what we observe happening, but on a smaller scale, in the Van Allen belt around Earth. The magnetic fields of Saturn, Uranus, and Neptune, discovered by the spacecraft that first passed close to these planets, work in a similar way, but are not as strong.

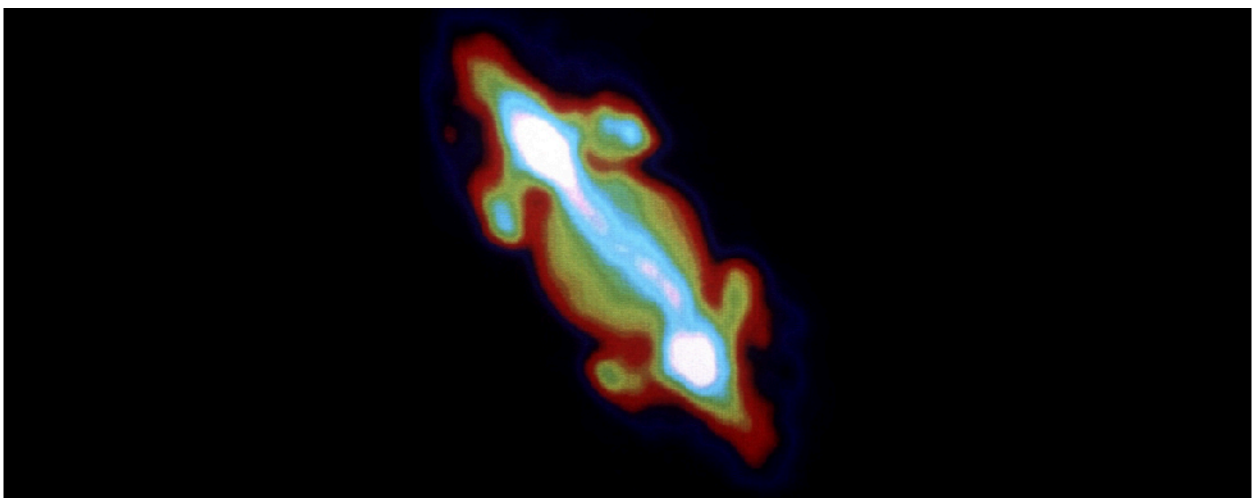

**Figure 11.8 Jupiter in Radio Waves.** This false-color image of Jupiter was made with the Very Large Array (of radio telescopes) in New Mexico. We see part of the magnetosphere, brightest in the middle because the largest number of charged particles are in the equatorial zone of Jupiter. The planet itself is slightly smaller than the green oval in the center. Different colors are used to indicate different intensities of synchrotron radiation. (credit: modification of work by I. de Pater (UC Berkeley) NRAO, AUI, NSF)

## LINK TO LEARNING

Learn more about **the magnetosphere of Jupiter (https://openstax.org/l/30NASAJupMag)** and why we continue to be interested in it from this brief NASA video.

Inside each magnetosphere, charged particles spiral around in the magnetic field; as a result, they can be accelerated to high energies. These charged particles can come from the Sun or from the neighborhood of the planet itself. In Jupiter's case, Io, one of its moons, turns out to have volcanic eruptions that blast charged particles into space and right into the jovian magnetosphere.

The axis of Jupiter's magnetic field (the line that connects the magnetic north pole with the magnetic south pole) is not aligned exactly with the axis of rotation of the planet; rather, it is tipped by about 10°. Uranus and Neptune have even greater magnetic tilts, of 60° and 55°, respectively. Saturn's field, on the other hand, is perfectly aligned with its rotation axis. Why different planets have such different magnetic tilts is not well understood.

The physical processes around the jovian planets turn out to be milder versions of what astronomers find in many distant objects, from the remnants of dead stars to the puzzling distant powerhouses we call quasars. One reason to study the magnetospheres of the giant planets and Earth is that they provide nearby accessible analogues of more energetic and challenging cosmic processes.

# 11.3 ATMOSPHERES OF THE GIANT PLANETS

## Learning Objectives

By the end of this section, you will be able to:

- Discuss the atmospheric composition of the giant planets
- Describe the cloud formation and atmospheric structure of the gas giants
- Characterize the giant planets' wind and weather patterns
- Understand the scale and longevity of storms on the giant planets

The atmospheres of the jovian planets are the parts we can observe or measure directly. Since these planets have no solid surfaces, their atmospheres are more representative of their general compositions than is the case with the terrestrial planets. These atmospheres also present us with some of the most dramatic examples of weather patterns in the solar system. As we will see, storms on these planets can grow bigger than the entire planet Earth.

## Atmospheric Composition

When sunlight reflects from the atmospheres of the giant planets, the atmospheric gases leave their "fingerprints" in the spectrum of light. Spectroscopic observations of the jovian planets began in the nineteenth century, but for a long time, astronomers were not able to interpret the spectra they observed. As late as the 1930s, the most prominent features photographed in these spectra remained unidentified. Then better spectra revealed the presence of molecules of methane ($CH_4$) and ammonia ($NH_3$) in the atmospheres of Jupiter and Saturn.

At first astronomers thought that methane and ammonia might be the main constituents of these atmospheres,