CHAPTER 2

The Ringed World

Saturn was the most distant planet that could be seen by ancient astronomers. Like Mercury, Venus, Mars and Jupiter, it appeared to be a bright, star-like wanderer that moved about the fixed stars in the night sky. For this reason, these celestial bodies were called “planetes,” the Greek word for “wanderers.” Little was learned about Saturn, besides its apparent celestial motions, until the telescope was invented in Holland in the early 1600s.

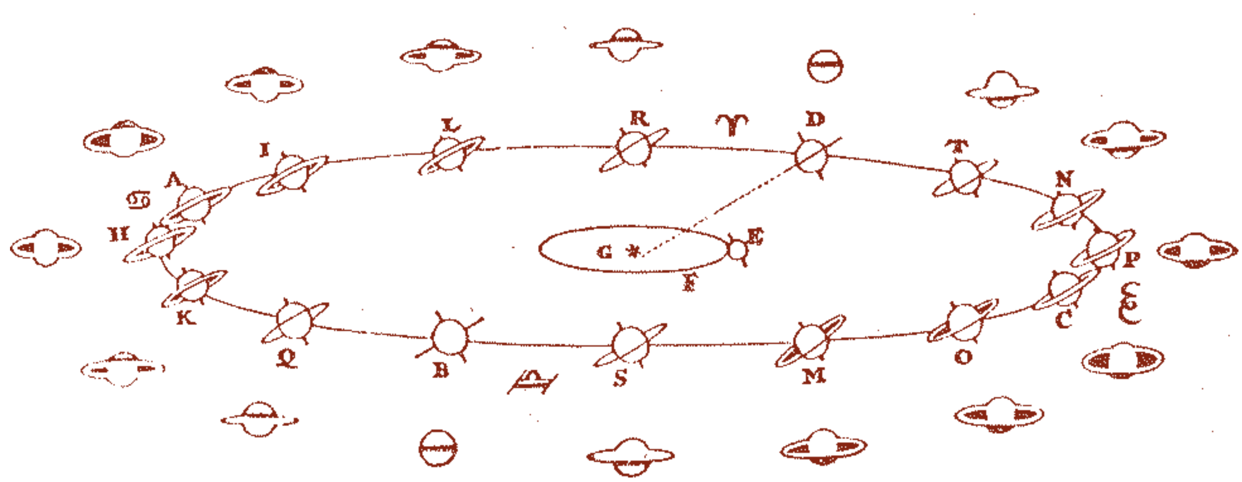
Historical Observations

In 1609, Galileo Galilei built his own telescope and put it to use in making observations of the night sky. In his initial observations of Saturn, Galileo thought he was seeing three planets because of the poor quality of the lenses of his telescope. By 1614, his notes indicated that he observed the rings for the first time — though he did not identify them as such.

The optical aberrations in early telescopic lenses prevented clear viewing. Because of the way Saturn’s rings appeared when viewed through early telescopes, observers spent the early years trying to understand what they interpreted as the planet’s odd shape and behavior. Some saw the rings as cup handles. By 1659, Christiaan Huygens had developed the concept of a planetary ring system, which helped the astronomers of the day understand what they were seeing.

Because of its dense cloud cover, all we can see of Saturn is the atmosphere — that is, if we do not look at the rings! Saturn has been a mystery to us since Galileo’s first telescopic observations in the early 17th century. Up to the time of the visits made by Voyagers 1 and 2, Saturn appeared as a fuzzy yellow ball with some visible banding and some pole darkening. We now know that the “surface” of Saturn is gaseous and that the patterns present are due to clouds in its gaseous envelope.

From Galileo’s time through the next 300 years, telescopes improved and more moons were discovered to be



In this diagram from his book, *Systema Saturnium*, Christiaan Huygens explained the inclination of Saturn’s rings according to the planet’s orbital position with respect to Earth.

orbiting Saturn. But not until the first spacecraft were able to fly by the planet did we really advance our knowledge of Saturn's atmosphere, complicated ring structure, magnetic field, magnetosphere and satellites.

So far, there have been three flyby missions to Saturn. Detailed information about Saturn's structure was obtained by these spacecraft. The first, Pioneer 11, flew by in August 1979. Pioneer's photopolarimeter made important measurements of Saturn's atmosphere, and the data could be assembled into low-resolution images. The atmosphere's appearance changes so rapidly, however, that the time required to take a picture was too long to capture the details. Only subsequent flyby missions by Voyager 1 in October 1980 and Voyager 2 in August 1981 were able to show us the complex structure of the atmosphere and its rapidly changing features. In addition to taking images, the Voyagers conducted many different experiments — the data collected greatly added to our knowledge of Saturn's interior structure, clouds and upper atmosphere.

The composition of planets in the solar system is largely controlled by their temperatures, as determined by their distances from the Sun. Refractory compounds (those with high melting points) were the first to condense, at temperatures around 1500 kelvins, followed by silicates at 1400 kelvins. These substances formed the rocky cores of the planets. While hydrogen is the predominant element in the universe and in our solar system, other gases are present, including water, carbon dioxide and methane, all of which condense below 500 kelvins. As ices, these predominate in the cooler, outer solar system. This gaseous material collected as envelopes around the planets and moons. (Where conditions are right, large quantities of water in its liquid state can form, as exhibited by Earth's oceans, Mars' flood plains and potentially beneath the surface of Europa, a moon of Jupiter.)

The large outer planets contain much of the primordial cloud's gases that were not trapped by the Sun. Hydrogen is the most abundant material in the Sun and in all the large gaseous planets — Jupiter, Saturn, Uranus and Neptune. Each of these giant planets — known as the "gas giants" — has many moons. These moons form satellite systems, suggesting that miniature solar systems formed around the gas giants by processes similar to those that formed the solar system itself.

Characteristics of Saturn

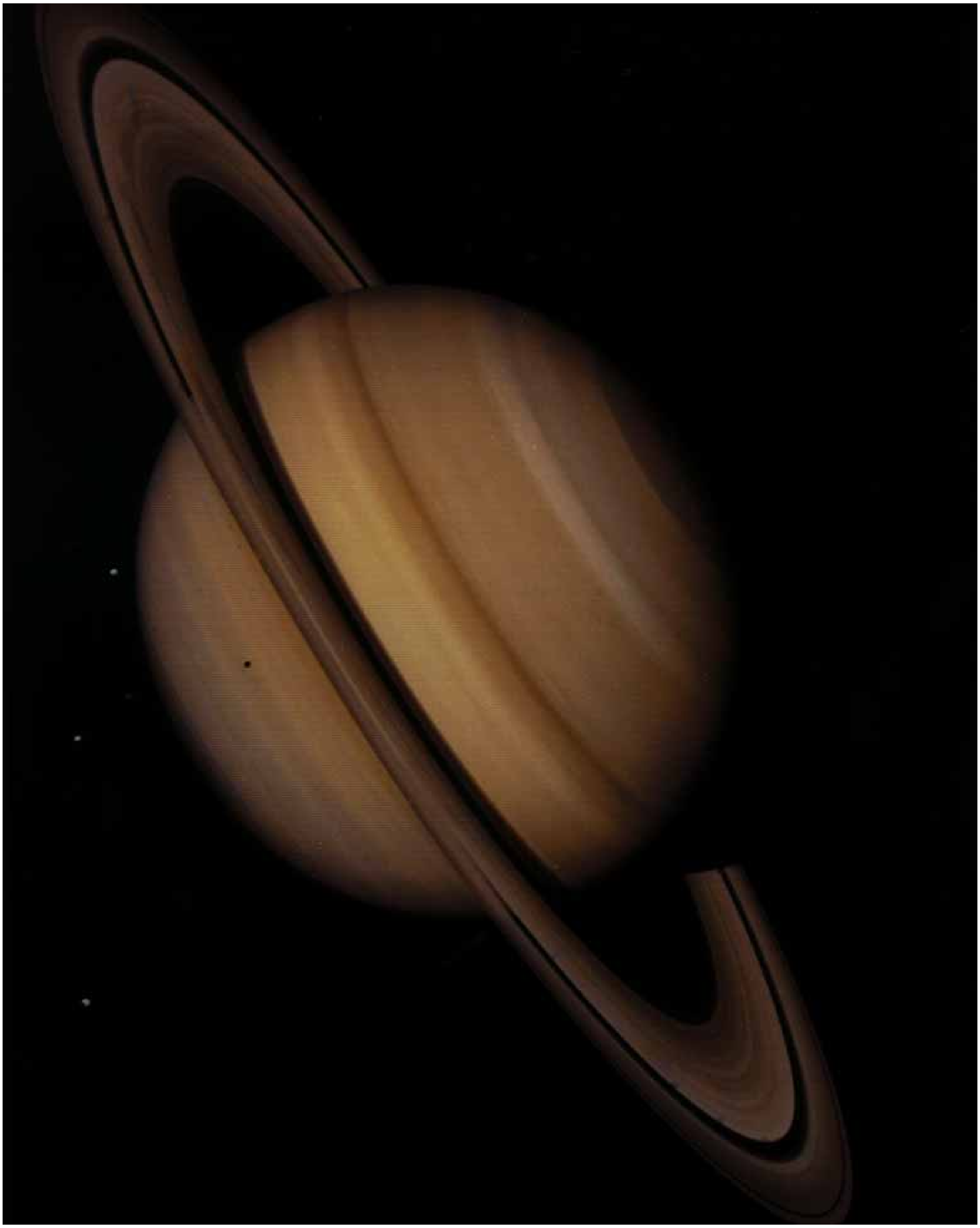
Cool and Slow. Saturn is the sixth planet from the Sun. It is nine-and-a-half times farther from the Sun than Earth. The diameter of the Sun viewed from Saturn is about one-tenth the size of the Sun we see from here on Earth. Sunlight spreads as it travels through space; an area on Earth receives 90 times more sunlight than an equivalent area on Saturn. Because of this fact, the same light-driven photoprocessing in Saturn's atmosphere takes 90 times longer than it would on Earth. You would not have to worry about getting a sunburn on Saturn!

Remembering the astronomer–mathematician Johannes Kepler's laws of planetary motion, the farther away from the Sun, the slower a planet travels in its orbit, and the longer it takes to complete its orbit about the Sun. Saturn travels at an average velocity of only 9.64 kilometers per second, whereas Earth travels at an average velocity of 29.79 kilometers per second. Saturn's yearly orbit about the Sun — a "Saturn year" — is equal to 29.46 Earth years. If you lived on Saturn, you would have only one birthday every 29-plus (Earth) years.

Since the orbit of Saturn is not circular but is elliptical in shape, its distance from the Sun changes during its orbital revolution around the Sun. The elliptical orbit causes a small change in the amount of sunlight that reaches the surface of the planet over the Saturn year, and may affect the planet's upper atmospheric composition over that period.

Slightly Squashed. Saturn's period of rotation around its axis depends on how it is measured. The cloud tops show a rotation period of 10 hours and 15 minutes at the equator, but 23 minutes longer at higher latitudes. A radio signal associated with Saturn's magnetic field shows a period of 10 hours and 39.4 minutes.

The high rotation rate creates a strong centrifugal force, causing an equatorial bulge and a flattening of



This Voyager 1 image shows Saturn's "squashed" appearance — the planet's equatorial bulge and flattened poles.

the planet's poles. As a result, Saturn's equator is 60,330 kilometers from the center, while the poles are only 54,000 kilometers from the center. Almost 10 Earths can be lined up along Saturn's equatorial diameter.

The Mysterious Interior

Low Density. To understand Saturn's interior and evolution, we must apply our basic knowledge of physics to observations of Saturn's volume, mass, gravity, temperature, magnetic field and cloud movement. The clues provided by this body of knowledge are not always easy to decipher, but as we gain more information on Saturn, we are more and more able to relate the pieces of the puzzle.

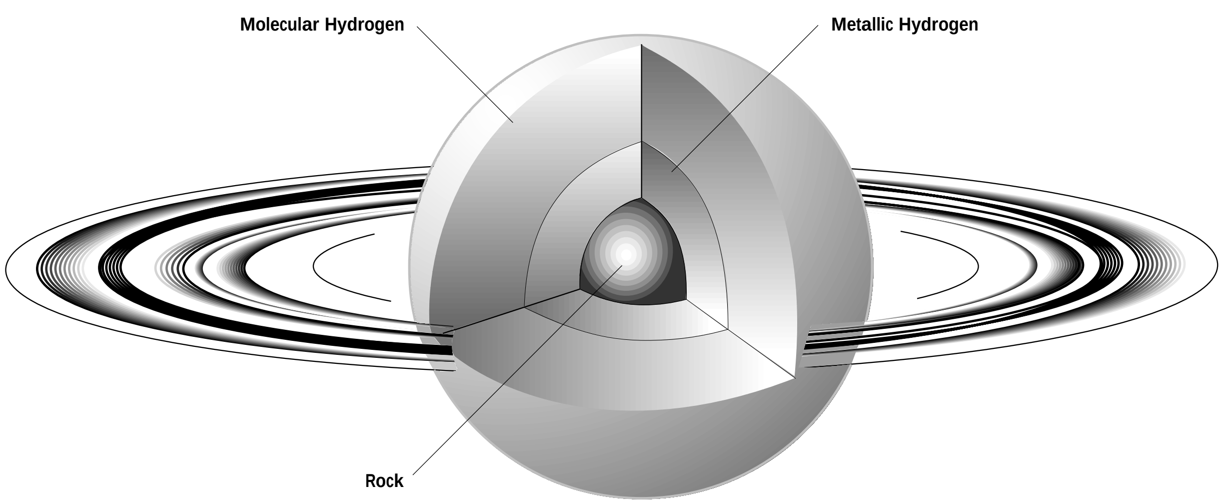
Saturn has the lowest density of all the planets, because of its vast, distended, hydrogen-rich outer layer. In the early 1900s, we thought that the giant planets might consist entirely of gas. Actually, the giant planets contain cores of heavy elements like iron as well as other components of refractory and silicate compounds, and thus have several times the mass and density of Earth.

Saturn's density is not uniform from its center to the surface — the density in the core is many times that of the surface. An understanding of this distribution is obtained through observations of planetary probes sent from Earth. Observations of the probe trajectories can be used to determine the density distribution throughout Saturn's interior.

The Rocky Core. Using data from the Voyager flybys, planetary scientists have put together a picture of Saturn's interior. We believe that Saturn has a molten rocky core of about the same volume as Earth, but with three or more times the mass of Earth's core. This increased density is due to gravitational compression resulting from the pressure of the liquid and atmospheric layers above the core.

The rocky core is believed to be covered with a thick layer of metallic liquid hydrogen, and beyond that, a layer of molecular liquid hydrogen. The great overall mass of Saturn produces a very strong gravitational field, and at levels just above the core the hydrogen is compressed to a state that is liquid metallic and conducts electricity. (On Earth, liquid hydrogen is usually made by cooling the hydrogen gas to very cold temperatures. On Saturn, liquid hydrogen is very hot, with temperatures of many thousands of kelvins, and is formed under several million times the atmospheric pressure found on Earth.) It is believed that this conductive liquid metallic hydrogen layer, spinning with the rest of the planet, is the source of Saturn's magnetic field — turbulence or convective motion in this layer may be creating the field.

A remarkable characteristic of Saturn's magnetic field is that its axis of rotation is the same as that of the planet. This is different from that of the five other known magnetic fields, of Mercury, Earth, Jupiter, Uranus and Neptune. Present theory suggests that when the axes of rotation and magnetic field are aligned, the magnetic field cannot be maintained.



This cutaway diagram shows the basic structure of Saturn's interior.

An Extended Atmosphere

From Liquid to Gas. Above the layer of liquid molecular hydrogen, there is a vast atmosphere that is only surpassed by the atmospheres surrounding Jupiter and our Sun. On Earth, there is a definite separation between the land, the oceans and the atmosphere, but Saturn has only layers of hydrogen that transform gradually from a liquid state deep inside to a gaseous state in the atmosphere, without a well-defined boundary. This is an unusual condition that results from the very high pressures and temperatures found on Saturn.

Because the pressure of the atmosphere is so great, at the point where the separation would be expected to occur, the atmosphere is compressed so much that it actually has a density equal to that of the liquid. This amazing condition is referred to as "supercritical." This can happen to any liquid and gas compressed to a point above critical pressure. Saturn thus lacks a distinct surface, so scientists make measurements from the cloud tops. The reference point is a pressure of one bar (or one Earth atmosphere, 760 millimeters of mercury).

The major component of Saturn's atmosphere is hydrogen gas. If the planet were composed solely of hydrogen, there would not be much of interest to study. However, the composition of Saturn's atmosphere includes six percent helium gas by volume and 0.0001 percent of other trace elements. Using spectroscopic analysis, scientists know that these atmospheric elements can interact to form ammonia, phosphine, methane, ethane, acetylene, methylacetylene and propane. Even a small amount is enough to freeze or liquefy and make clouds of ice or rain possessing a variety of colors and forms.

Two satellites orbit far above the raging storm clouds of Saturn in this false-color image taken by Voyager 1.

With the first pictures of Saturn taken by the Voyager spacecraft in 1980, we could see that the clouds and the winds were almost as complex as those found on Jupiter just the year before. There has been an effort to label the belts and zones seen in Saturn's cloud patterns. The banding results from temperature-driven convective flows in the atmosphere, very much the same process that occurs in Earth's atmosphere, but on a grander scale and with a different heat source.

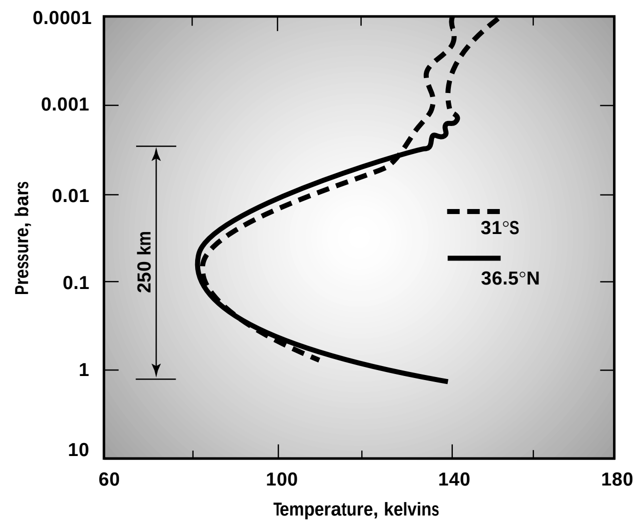
Saturn has different rotation rates in its atmosphere at different latitudes. Differences of 500 meters per second were seen between the equator and nearer the poles, with higher speeds at the equator. This is five times greater than the wind velocities found on Jupiter.

The Exosphere. Like all planets and moons with atmospheres, Saturn's outermost layer of atmosphere is extremely thin. The exosphere is the transition from lower layers to the very tenuous gases and ions within the magnetosphere, which extends out to the moon Titan and beyond. Since its density is so low, the exosphere is easily heated by absorption of sunlight. At the outer edge of the exosphere, the temperature of Saturn's atmosphere is between 400 and 800 kelvins, cooling closer to its base.

The gases in the exosphere are heavily bombarded with light and thus dissociate to the atomic level, that is, all the chemicals in the exosphere are separated into atoms or atomic ions. This material has no way to dissipate the energy absorbed from sunlight except through a rare collision with another atom. Absorbed solar photons heat the exosphere up and the collisions cool it down. How fast the exosphere heats or cools depends upon how far away it is from the bulk of the atmosphere.

The Ionosphere. Lower in the atmosphere, below the exosphere, is the ionosphere. It is characterized by a large abundance of electrons and ions. There are equal numbers of negatively charged electrons and positively charged ions, because the electrons and the ions are formed at the same time. When a high-energy photon of light is absorbed by a neutral or ion, a negative electron is energized to escape, leaving an ion behind with an equal amount of positive charge. The maximum number of charged particles in the ionosphere occurs at a distance of 63,000 kilometers from the planet center, or 3000 kilometers above the one-bar pressure level.

Between the exosphere and the middle of the ionosphere, the predominant ions are H^+, H_2^+, and H_3^+. In the lower ionosphere, where there is an increase in pressure, more complicated hydrocarbon ions predominate. The number of ions present is only a very small percentage of the molecules in the atmosphere, but as in Earth's atmosphere, the ionosphere has an important influence. The ionosphere is like a pair of sunglasses for the planet, filtering out the more energetic photons from sunlight. These energetic photons are the cause of the ionization.



Voyager 2 measurements showed the nearly identical atmospheric structure at two different positions on Saturn.

Cloud Decks. Approaching the planet and from a distance, the Voyager spacecraft could only see a slightly squashed, fuzzy yellow sphere. As the spacecraft drew nearer to Saturn, light and dark bands parallel to the equator appeared. Closer yet, cyclonic storms could be seen all over the planet. Following the paths of the storms, scientists could measure the velocities of the winds. Scientists observed the tops of clouds covering the "surface" of Saturn, which indicated very high wind speeds at the equator and giant storm patterns in bands around the planet. There were holes in the clouds, and more layers below.

A minimum temperature is reached in Saturn's atmosphere at about 250 kilometers above the one-bar level. At this altitude, the temperature is about 82 kelvins. At such low temperatures, the trace gases in the atmosphere turn into liquids and solids, and clouds form. The highest clouds are associated with ammonia ice at the one-bar level, ammonium sulfide at 80 kilometers below this point, and water ice at 260 kilometers below the ammonia clouds. The gases are stirred up from the lower altitudes and condense into ice grains because the temperature is low and the pressure has dropped to about one bar. At this pressure, the condensation process starts and the ammonia, ammonium sulfate and water take the form of ice crystals.

Haze layers are also observed above the temperature minimum, at pressures of 0.1 and 0.01 bar. Both the origin and composition of these hazes are unknown.

Winds and Weather

Saturn is completely covered with clouds. The cloud tops show the effects of the temperature, winds and weather occurring many kilometers below. Hot gases rise. As they rise, they cool and form clouds. As these gas clouds cool, they begin to sink; this convective motion is the source of the billowy clouds we see in Saturn's cloud layer. The cyclonic storms we observe in the planet's cloud tops are much like the smaller versions we see in our daily satellite weather reports on Earth.

The horizontal banding in Saturn's clouds is a result of the different wind speeds at different latitudes. The fastest winds are at the equator; the banding results from the wind shear between different zones of latitude. One possible model suggests that the atmosphere is layered in cylinders that rotate at different rates and whose axes parallel the planet's axis. If this is true, there should be other notable consequences that will be revealed in future observations of Saturn.

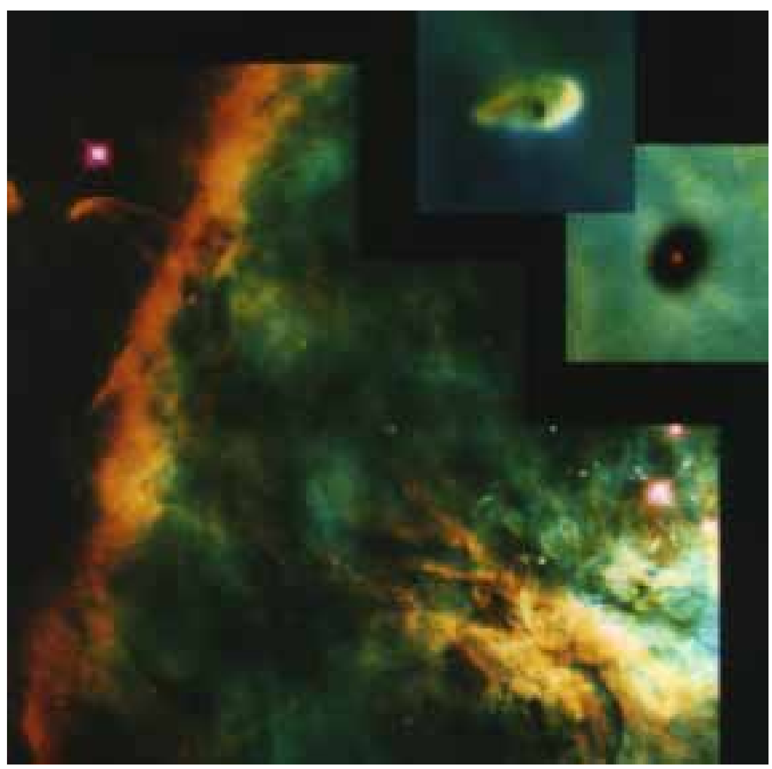
There are variations in temperatures on Saturn, as well, which are the driving forces for the winds and thus cloud motion. The lower atmosphere is hotter than the upper atmosphere, driving the vertical motion of gases, and the equator is warmer than the poles because it receives more direct sunlight. Temperature variations combined with the planet's rapid rotation rate drive the horizontal motion of winds in the atmosphere.

A Comparison to Jupiter

Saturn is similar to Jupiter in size, shape, rotational characteristics and moons, but Saturn is less than one-third the mass of Jupiter and is almost twice as far from the Sun. Saturn radiates more heat than it receives from the Sun. This is true of Jupiter as well, but Jupiter's size and cooling rate suggest that it is still warm from the primordial heat generated from condensation during its formation. The smaller Saturn, however, has had time to cool, so some mechanism — such as helium migration to the core

A STAR IS BORN

Studies of star formation indicate that our solar system formed out of a collection of gases and dust, drawn together by gravitational attraction and condensed over millions of years into many stars. The giant gas cloud condensed into rotating pools of higher density in a process called gravitational collapse, because as condensation proceeds, it accelerates. These rotating pools of material condense more rapidly until their temperatures and densities are great enough to form stars. Surrounding each new star, the leftover material flattens into a disk rotating approximately in the plane of the star's equator. This material can eventually form planets — apparently what occurred to form our own solar system. This image, from the Hubble Space Telescope's Wide Field and Planetary Camera 2, shows a part of the Orion Nebula, which is known as a "nursery for young stars." The inset images at far right are possible examples of young stars.



— must be found to explain its continuing radiation of heat.

From Voyager measurements, we learned that Saturn's ratio of helium to molecular hydrogen is 0.06, compared to Jupiter's value of 0.13 (which is closer to the solar abundance and that of the primordial solar nebula). The helium depletion in Saturn's upper atmosphere is believed to be due to helium raining down to the lower altitudes; this supports the concept of helium migration as the heat source in Saturn. Measurements of the planet's energy, radiation and helium abundance will help explain the residual warmth we observe.

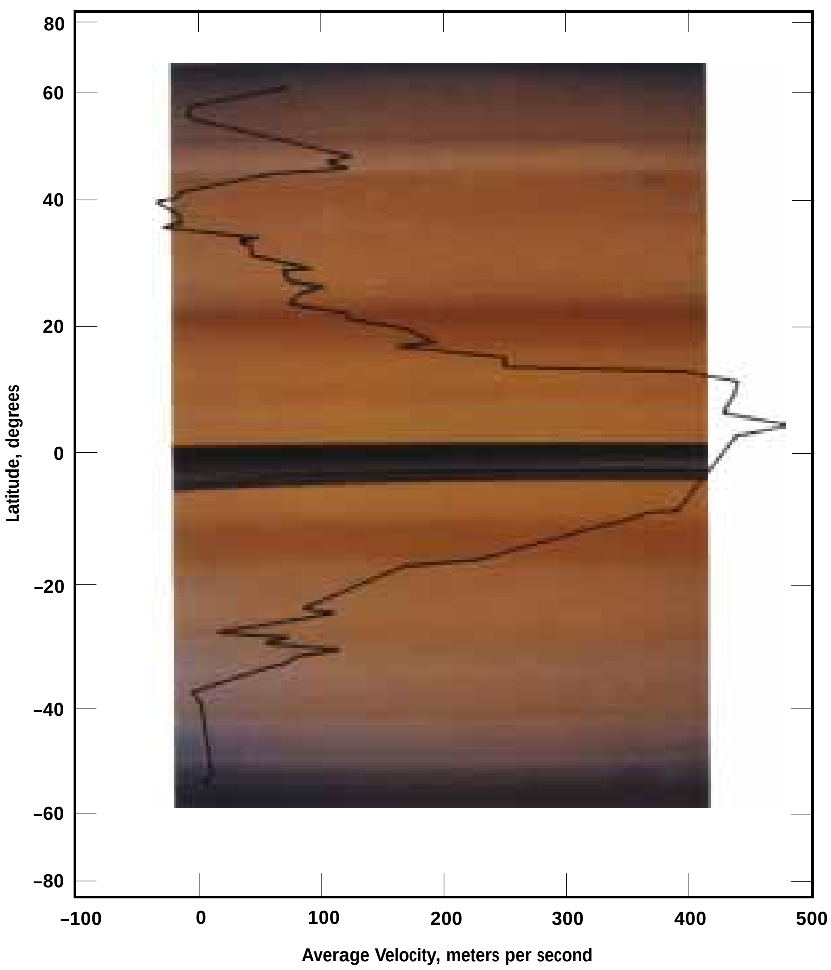
Saturn's "surface" features are dominated by atmospheric clouds. They are not as distinct as Jupiter's clouds, primarily because of a haze layer covering the planet that is a result of the weaker insolation from the Sun. This reduced solar radiation leads to greater wind velocities on Saturn. Both Saturn's and Jupiter's weather are driven by heat from below.

Cassini's Global Studies

The Cassini Orbiter's remote-sensing instruments will be the primary data gatherers for global studies of Saturn's atmospheric temperatures, clouds, and composition. Each instrument will provide unique types of data to help solve the puzzles of Saturn's atmosphere.

The Composite Infrared Spectrometer (CIRS), operating in the thermal infrared at very high spectral resolution, is specifically designed to determine temperatures and will spend long periods scanning Saturn's atmosphere. Over the course of a Saturn day, the whole planet will rotate through this instrument's field of view, providing data that will produce a thermal map. Such measurements will help us evaluate the amount of solar heating as compared with the heating generated from the planet's interior. In addition, CIRS can independently measure the temperatures of the different gases composing Saturn's atmosphere. This will give information about how the temperature of Saturn's atmosphere changes at different depths.

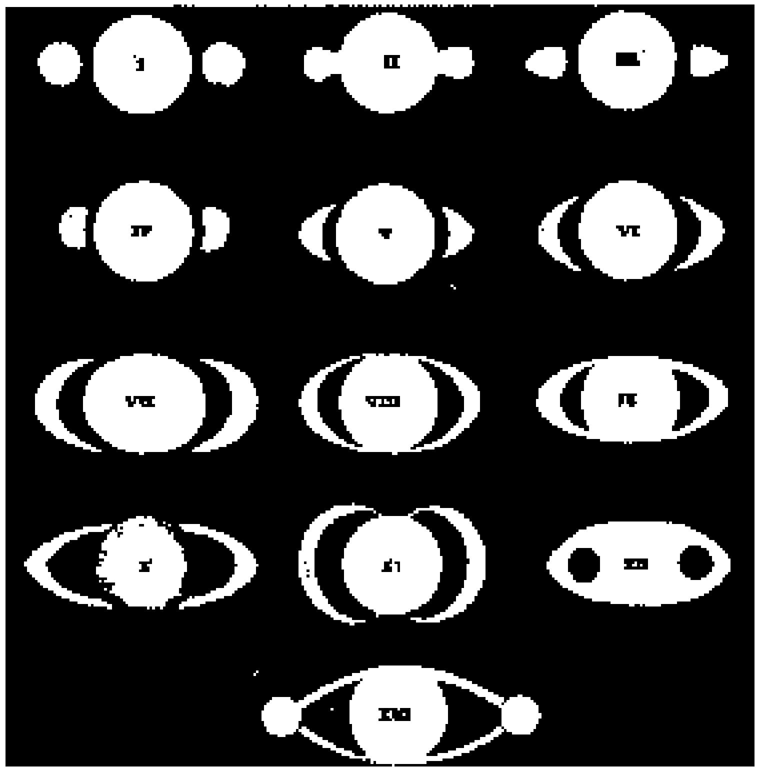
Radio science experiments use the spacecraft's radio and ground-based antennas as the science instrument. The Cassini Orbiter will send microwave radio signals through the atmosphere of Saturn to Earth; Saturn's ionosphere and atmosphere will change the signal as it passes through. The radio science "probe" will be used to measure the electron density, temperature, pressure and winds in the ionosphere. Temperature data from radio science experiments depend on the composition of the atmosphere in a unique manner compared with other instruments; thus, the most sensitive determination of helium abundance will be obtained by combining radio science data with measurements from the CIRS.



The fastest winds on Saturn are at the equator, here shown surpassing 400 meters per second.

IN THE EYE OF THE BEHOLDER

Taken from Christiaan Huygens' *Systema Saturnium*, these early drawings of Saturn represent the views of: I. Galileo, 1610; II. Scheiner, 1614; III. Riccioli, 1614 or 1643; IV–VII. Hevel; VIII, IX. Riccioli, 1648, 1650; X. Divini, 1646–1648; XI. Fontana, 1636; XII. Biancani, 1616; XIII. Fontana, 1644–1645. Some of the drawings, such as IX, had a very ring-like appearance years before Huygens' theory was accepted.



Similar measurements made by the Ultraviolet Imaging Spectrograph (UVIS) and the Visible and Infrared Mapping Spectrometer (VIMS) as the Sun disappears behind Saturn (as seen from the Orbiter) are also very informative. These experiments will observe the atmosphere's variation in composition and opacity with depth by measuring the intensities of various colors of sunlight as the Sun sets into haze and clouds. Each molecule in Saturn's atmosphere can be identified by its unique absorption and emission of the sunlight.

Cassini–Huygens' three spectrometers complement each other in measurements of atmospheric composition. The UVIS and the VIMS measure chemical composition at wavelengths spanning the ultraviolet and near infrared — useful in determining many expected atmospheric components. The CIRS and the UVIS can measure atomic composition as well; the former can delineate the atomic composition of molecules, while the latter can measure atoms directly. The important abundances of deuterium and other interesting isotopes will be investigated to shed light on the origin of our solar system.

The UVIS will follow up on Hubble Space Telescope observations with studies of the energetics of Saturn's aurora. The VIMS and potentially the CIRS can contribute also, and the imaging system will monitor the aurora's changing morphology.

The Imaging Science Subsystem (ISS) will play a major role in understanding the dynamics of Saturn's clouds and weather systems. With wind speeds of 1800 kilometers per hour at the equator, the cloud bands seen beneath the haze layer are subject to considerable turbulence. Indeed, the bands themselves are defined by the winds, separated by zones of high wind shear. In addition, storms can be discerned among the bands, and their dynamics are of considerable interest. Images of the same region made with different filters can be interpreted to indicate the altitudes of various phenomena.

"Saturn-annual" white spots, which appear at approximately 30-year intervals, are not expected during the portion of the cycle when Cassini is studying the planet, but other white spots may fortuitously appear and will be studied by all the optical remote-sensing instruments. Cassini may be able to confirm the theory that the white spots are caused by the upwelling and condensation of ammonia-ice crystals in the atmosphere.

By carefully tracking the Cassini Orbiter's motion around Saturn, data on the deep layers — all the way to the core — of Saturn can be acquired. In these studies, radio signals from the spacecraft will be monitored for changes, especially Doppler shifts of frequency that are different from those predicted from a simple base model. Using the new measurements from the Cassini Orbiter, more detailed models of the internal structure of Saturn will be constructed.