Uranus, Neptune, Pluto and How to Observe Them

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Richard W. Schmude, Jr.

Uranus, Neptune, Pluto and How to Observe Them

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This book is dedicated to the many people who have helped me along the way: First, to my father and mother, Richard and Winifred Schmude, who first showed me the stars and answered my many science questions; next, to the many fine teachers and professors that I have had along the way; also, to all of the fine people at Optec, Inc., who make a great line of photometers without which I would not have been able to carry out much outer solar system research; and finally, to the many friends who have encouraged me along the way, including Jim Fox and Jerry Sherlin of the Astronomical League, Donald Parker, John Westfall, Ken Poshedly, Richard Jakiel, and Walter Haas of the Association of Lunar and Planetary Observers, Richard McKim and John Rogers of the British Astronomical Association, and Kim Hay of the Royal Astronomical Society of Canada.

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Author's Note

I became interested in astronomy initially when I saw what appeared to be a countless number of stars from my parent's home in Cabin John, Maryland. I was no older than six when I had this life-changing view of the night sky. I purchased my first telescope when I was 15 years old; it had an aperture of 1.5 cm and a magnification of 8X. I enjoyed looking at the Moon and at other distant objects through this telescope. I was also able to let others look through this small wonder, including a couple of siblings and at least one neighbor.

Even as a young boy, I had been fascinated with all of the planets. My first view of Uranus was from my parent's home near Tomball, Texas, on March 20, 1987. In 1989, I began estimating the brightness of Uranus with binoculars, and, a year later, John Westfall asked me to be the outer planets coordinator for the Association of Lunar and Planetary Observers (ALPO). With this appointment, I purchased an SSP-3 solid-state photometer from Optec Inc. and began carrying out brightness measurements of Uranus and Neptune.

Our knowledge of the outer Solar System has increased tremendously in the last 40 years. As a boy, I would often look at astronomy textbooks to learn about the planets. On many occasions, I noticed question marks next to Uranus, Neptune, and Pluto in tables summarizing planetary data. The question marks were there because we did not know much about these objects in the late 1960 s. Later, in college, I remember that there was just one page devoted to Uranus, Neptune, and Pluto in my college astronomy textbook; this was in 1981. Once again, we did not know much about these outer worlds and, hence, there was little to write about. With the Voyager 2 flybys of Uranus (1986) and Neptune (1989), we have learned a great deal more about them. The Hubble Space Telescope, electronic cameras, and advanced computer technology have also given us more information about Pluto. In the early twenty-first century, humankind has gained enough information about these distant planets to justify the writing and publication of this book.

This book is broken down into two major sections. The first section summarizes our current knowledge of Uranus (Chapter 1), Neptune (Chapter 2), and Pluto (Chapter 3). The second section describes observing projects that one can carry out with small telescopes and binoculars (Chapter 4), medium-sized telescopes (Chapter 5), and large telescopes (Chapter 6). Finally, an appendix, a bibliography, and an index are included.

Two organizations that are engaged in serious studies of the remote planets are the British Astronomical Association (BAA) and the Association of Lunar and Planetary Observers (ALPO). The current remote planets' coordinator of the BAA is Roger Dymock, who can be reached at: roger.dymock@ntlworld.com, and the current remote planets coordinator of the ALPO is myself, Richard W. Schmude, Jr. I can be reached at: Schmude@gdn.edu. If one makes observations of one of these distant worlds, please let one or both of us know about it. Many thanks!

About the Author

Dr. Richard W. Schmude, Jr., was born in Washington, D.C., and attended public school in Cabin John, Maryland; Los Angeles, California; and Houston, Texas. He graduated from Texas A & M University with a Bachelor's degree in Chemistry, and a few years later, another Bachelor's degree in Physics. Later, he obtained a Master's degree in Physical Chemistry and a Ph.D. in Physical Chemistry. He worked at Los Alamos National Laboratory as a graduate research assistant from 1990 to 1992. While at Los Alamos, he purchased his first photometer and began measuring the brightness of Uranus and Neptune.

In 1990, Richard was appointed Coordinator of the Remote Planets section of the Association of Lunar and Planetary Observers. He began teaching at Gordon College in Barnesville, Georgia, in 1994 and has taught chemistry, physics, astronomy, and physical science there ever since. He has published over 100 scientific papers in many different journals and has given many talks and workshops to community organizations.

Chapter 1

The Uranus System

Introduction

Since its discovery in 1781, Uranus has been an object of mystery. It lies 2,900 million kilometers (1,800 million miles) from our Sun. This great distance of the seventh planet, along with its long seasons (about 21 years each), are two reasons why Uranus has been slow to reveal its secrets. Thanks to dedicated scientists and engineers, along with the availability of modern equipment, the growth of our knowledge of Uranus has accelerated since the mid-1980 s. Figure 1.1 shows a series of images of Uranus and its rings made by operators of the modern Keck telescope equipped with advanced imaging technology. Table 1.1 lists a few characteristics of this planet.

Figure 1.2 show the number of reports dedicated to Uranus, Neptune, and Pluto appearing in a journal on the Solar System. The increase in knowledge is due primarily to three factors: (a) Voyager 2, (b) the development of modern astronomical telescopes and equipment and (c) a sharp improvement in computer technology.

In this chapter, we will discuss the atmosphere of Uranus followed by discussions of its bulk composition and interior. This will be followed by a discussion of Uranus's magnetic environment, rings, and moons.

Chapters 2 and 3 present a summary of our current knowledge of the Neptune and Pluto systems, respectively.

Atmosphere

Earth and Uranus have dynamic atmospheres. Both planets obtain most of their heat from the Sun and undergo a cycle of seasons. In this section, we will discuss an altitude reference point for Uranus, followed by a discussion of the gases, clouds, and winds in the Uranian atmosphere. Before these traits are discussed, though, an altitude reference point must be established for Uranus.

All altitudes on Earth are given with respect to sea level; however, Uranus does not have a visible ocean. Hence, an alternative way of describing altitudes must be established. The general convention for Uranus and Neptune is to describe the altitude in terms of the local atmospheric pressure; for example, a cloud at the "2.0 bar level" will be at an area where the pressure is 2.0 bar. One "bar" of pressure

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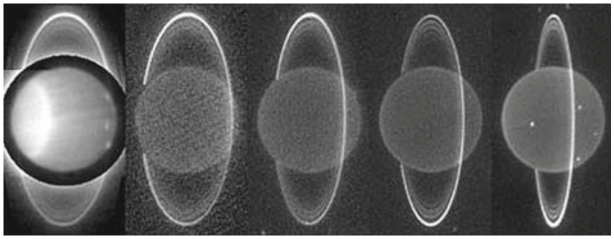

Figure 1.1. Five near-infrared images of Uranus and its rings made with Earth-based telescopes. The rings are easy to see because the methane in Uranus's atmosphere absorbs most of the near-infrared light hitting Uranus causing it to be very dark. The rings are closing up due to the changing orientation of Uranus as seen from Earth. (Credit: Imke de Pater, Heidi Hammel and Sarah Gibbard.)

Table 1.1. Characteristics of Uranus

Characteristic	Value
Equatorial diameter	25,559 km (1 bar level)
Polar diameter	24,974 km (1 bar level)
Surface area	8.08×10^9 km^2 (1 bar level)
Mass	8.68×10^{25} kg
Density	1.27 g/cm^3
Period of rotation	17.24 hours
Period of revolution around the Sun	84.0 years
Inclination	82.2°
Average distance from the Sun	19.19 au
Average distance from Earth at opposition	18.19 au
Orbital inclination	0.8°
Orbital eccentricity	0.05
Ellipticity (or polar flattening)	0.0229
Magnetic field strength at 1 bar level	0.1 to 1.0 Gauss

is about what we experience at sea level here on Earth. For the purpose of defining the diameter of Uranus, an atmospheric pressure of 1.0 bar is selected. Therefore, both diameters in Table 1.1 correspond to an atmospheric pressure of 1.0 bar. The 2.0 bar level is at a lower altitude than the 1.0 bar level. Throughout this book, altitudes are either given with respect to the 1.0 bar level or in terms of the local atmospheric pressure.

Some of the terms used for our atmosphere can also be used for Uranus; however, one must be careful. As an example, Uranus does not have a well-defined mesosphere, or if it does, we have not been able to accurately measure its temperature and density.

The atmosphere of Uranus can be divided into three regions based on altitude, namely, the upper, middle, and lower atmosphere. Each of these regions is discussed below.

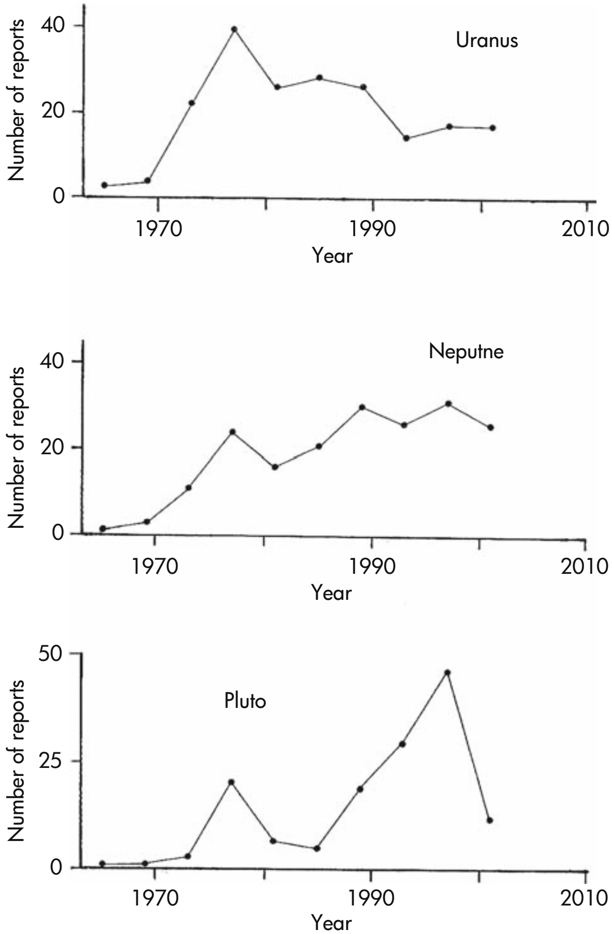

Figure 1.2. Three graphs showing the number of reports that discuss Uranus, Neptune and Pluto appearing in the professional Journal *Icarus* from 1963 to 2004. Each point shows the number of reports published in three-year increments starting with 1963 to 1965. (Credit: Richard W. Schmude, Jr.)

Upper Atmosphere

The upper atmosphere lies above the homopause, which is near the 0.02 mbar (millibar) level. Above the homopause, the percentage of heavier components, such as helium and methane, drop off more quickly with increasing altitude than lighter components, such as atomic hydrogen.

The upper atmosphere contains two types of matter – plasma and gas – and, at some locations; each component exists in the same area. The gaseous component is made up of neutral species. This component contains the thermosphere and exosphere. The ionosphere contains electrons and positively charged ions such as H^+. Figure 1.3 shows the different parts of the upper atmosphere.

Plasma consists of subatomic particles and ions. Its charge is usually balanced, which means that it has an equal amount of positively and negatively charged

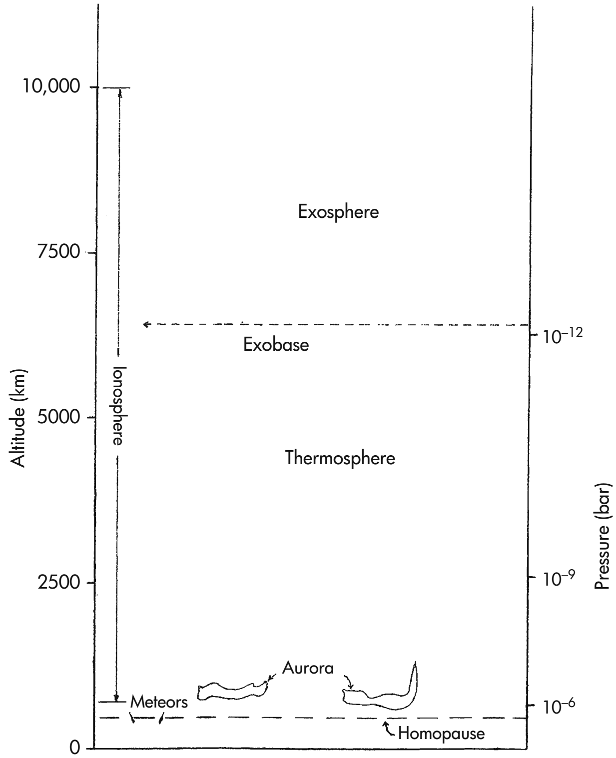

Figure 1.3. A diagram of Uranus's upper atmosphere. The altitude is with respect to the 1.0 bar level. Different levels of pressure are shown at the right. (Credit: Richard W. Schmude, Jr.)

particles. Protons have a positive charge and electrons have a negative charge. Atoms or molecules that have more electrons than protons are called anions, whereas those with more protons than electrons are called cations. Cations and anions are both called ions and can make up a large fraction of some plasmas.

Most of our information of Uranus's ionosphere comes from Voyager 2. This probe passed Uranus in 1986, when the Sun was near a minimum in its sunspot cycle. We know that Earth's ionosphere thins out near solar minimum, and there is a chance that this may have occurred for Uranus in 1986.

Uranus's ionosphere lies at altitudes of 600– ~10,000 km. This altitude range contains both neutral species and charged particles. The ionosphere refers only to the charged particles, such as electrons and protons. Its electron density ranges from ~100 to over 10,000 electrons/cm^3. The peak electron density is at an altitude of 1,500 km; for a comparison, the gas density at this altitude is around 10^{12} molecules/cm^3. There are over 1 million neutral atoms for every ion or electron at this altitude. Despite this, the charged particles may be the dominant heat source at altitudes of 600–10,000 km.

The neutral gas in the upper atmosphere can be broken down into three layers: the bottom layer, which has pressures of between about 2×10^{-5} and 1×10^{-6} bar, then the thermosphere, which has approximate pressures of between about 10^{-6} and 10^{-12} bar, and the exosphere, which has pressures below 10^{-12} bar. Each of these layers is described below, starting with the bottom layer. See Figure 1.3.

Table 1.2. A few photochemical and ionic reactions that are believed to take place in the upper and middle atmospheres of Uranus; the symbol for an electron is e^-

Upper Atmosphere	
H_2 + ultraviolet light $\rightarrow$ H + H	(1)
H_2 + high energy ultraviolet light $\rightarrow$ H_2^* + low energy light	(2)
H_2 + high energy e^- $\rightarrow$ H_2 + low energy e^- + ultraviolet light	(3)
*Hydrogen is in a high energy (or excited) state.	
Ionosphere	
$H_2 + e^- \rightarrow H^+ + H + 2\,e^-$	(4)
$He + e^- \rightarrow He^+ + 2\,e^-$	(5)
Middle atmosphere (or stratosphere)	
CH_4 + ultraviolet light $\rightarrow$ CH_2 + H + H	(6)
CH_4 + ultraviolet light $\rightarrow$ CH_2 + H_2	(7)
CH_4 + ultraviolet light $\rightarrow$ CH + H + H_2	(8)
C_2H_2 + ultraviolet light $\rightarrow$ C_2H + H	(9)
$CH_4 + CH \rightarrow C_2H_4 + H$	(10)

The bottom layer includes the homopause and the transition between the middle and upper atmosphere. Several important processes occur in this layer. Small pieces of space dust falling into Uranus's atmosphere undoubtedly burn up there and would appear as meteors. The aurora also occurs in this layer. A large amount of ultraviolet light is emitted there as well. Astronomers believe that the two sources of this ultraviolet emission are fluorescence (reaction 2 in Table 1.2) and high-energy electrons colliding with neutral species, like hydrogen (H_2), creating ultraviolet light (reaction 3 in Table 1.2). Fluorescence is a process whereby material absorbs light with a high energy and then emits lower energy light.

Astronomers can probe the bottom layer of the upper atmosphere using Earth-based stellar occultation data. Occultation data show that there is a small temperature increase at around the 3-μbar (microbar) level. One group of astronomers suggests that this may be due to material falling from the rings, which is heated by sunlight.

The thermosphere has several distinct characteristics. It starts at an altitude of 600 km and extends upwards for a few thousand kilometers. This region gets much of its heat from the ionosphere. At an altitude of 1,500 km, the temperature is approximately 500–600 K and rises with increasing altitude. Another characteristic of the thermosphere is that its composition changes with altitude. In one study, the thermosphere is reported to have over 99% molecular hydrogen (H_2), with just traces of helium and atomic hydrogen (H) at an altitude of 1,500 km. Furthermore, the composition is predicted to change to 90% H_2 and 10% H at an altitude of 5,000 km and at altitudes above 10,000 km, H is predicted to be more abundant than H_2. The reason for this is that H has a lower molar mass (1 g/mole) than H_2 (2 g/mole). Gases with high molar masses thin out quicker at increasing altitudes in the thermosphere than those with low molar masses. The thermosphere emits some ultraviolet light.

Above the thermosphere lies the exosphere, which has characteristics different from the lower atmospheric layers. One group reports that this layer scatters ultraviolet light out to at least 70,000 km above the 1.0 bar level. Ring particles experience drag forces from the exosphere. The outer portion of the exosphere is often called the corona.

The outer part of the exosphere is far from Uranus. Atoms in this area that are moving from Uranus are unlikely to collide with other atoms and thus may escape from the planet. Atoms below the exosphere, which are moving from Uranus, however, are in a dense enough gas that they will probably collide with other atoms. As a result, gases below the exosphere are much less likely to escape than those in the exosphere. The bottom border of the exosphere is the exobase; for Uranus, this is about 6,400 km above the 1.0 bar level.

Middle Atmosphere (Stratosphere)

The middle atmosphere is Uranus's stratosphere. This is a region that lies above the 0.1 bar level, and its temperature rises with increasing altitude. The upper boundary of the stratosphere is difficult to pinpoint due to the problem of identifying Uranus's mesosphere; let's call it the 0.020 mbar level, which is near the homopause. Unlike the upper atmosphere, the chemical composition of the stratosphere does not change much with altitude. This is because gas mixing is more important than at higher altitudes.

The stratosphere is often transparent to visible light for two reasons. First, it often lacks opaque clouds, and second, it is made up mostly of hydrogen and helium; both of these gases are transparent to this light at low pressures. The composition of the stratosphere is listed in Table 1.3. One reason why there are no gases in significant quantities in the stratosphere besides hydrogen, helium, and methane is because of its low temperature. Most compounds (such as ammonia, water, and carbon dioxide) that are pushed upwards would condense at the low temperatures ($\sim$52 K) at the bottom of the stratosphere. Essentially, this area acts like a cold trap. Methane's vapor pressure at 52 K is $\sim 10^{-5}$ bar, which is high enough for some of that material to pass through the coldest part of the stratosphere as a gas.

Table 1.3. Composition of Uranus's middle atmosphere (or stratosphere)

Component	Percentage by Volume	Mass Fraction
Molecular Hydrogen (H_2)	85%	74%
Deuterated Hydrogen (HD)	Trace	Negligible
H_3^+	Trace	Negligible
Helium (He)	15%	26%
Methane (CH_4)	0.01 to 0.001%	$<$0.1%
Methyl radical (CH_3)	Trace	Negligible
Methane with deuterium (CH_3D)	Trace	Negligible
Acetylene (C_2H_2)	Trace	Negligible
Ethene (C_2H_4)	Trace	Negligible
Ethane (C_2H_6)	Trace	Negligible
CH_3C_2H or C_3H_4	Trace	Negligible
Diacetylene (C_4H_2)	Trace	Negligible
Carbon Monoxide (CO)	Trace	Negligible
Carbon Dioxide (CO_2)	Trace	Negligible
Water (H_2O)	Trace	Negligible

Several photochemical reactions occur in the middle atmosphere, and a few of these are listed in Table 1.2. Essentially, the small amount of methane and other hydrocarbons react with sunlight to produce a variety of hydrocarbon molecules. Many of these are present in trace quantities and are listed in Table 1.3. These gases condense at the low stratospheric temperatures and create haze. The haze particles are believed to form when material condenses onto microscopic solid particles. Two areas at 0.5 mbar and 13 mbar have higher temperatures than the surrounding altitudes. The condensation temperatures of diacetylene (C_4H_2) and ethane (C_2H_6) are near the 0.5 and 13 mbar levels. These two gases may condense, forming haze layers, which then absorb extra sunlight, thus causing higher temperatures. Additional chemical reactions may take place also on the haze particles. In fact, the haze particles probably contain some hydrocarbon molecules such as C_4H_2 and C_6H_2, which have at least four carbon atoms.

A thorough analysis of Voyager 2 images, especially at high solar phase angles, has given us information about the haze particles near Uranus's south polar region at that time (1986). One group reports that their calculations are consistent with the haze having a low optical depth for visible light, which means that it transmits almost all of this type of light. A second group reports that the haze particles near the 1.0 mbar level have diameters of $\sim$0.01 μm, but, as they fall, they merge with one another, growing to about ten times their original diameters. It takes haze particles several years to fall into the warmer parts of the troposphere.

Methane is recycled in Uranus's atmosphere through the methane cycle. See Figure 1.4. Essentially, methane is destroyed by ultraviolet light and fast-moving

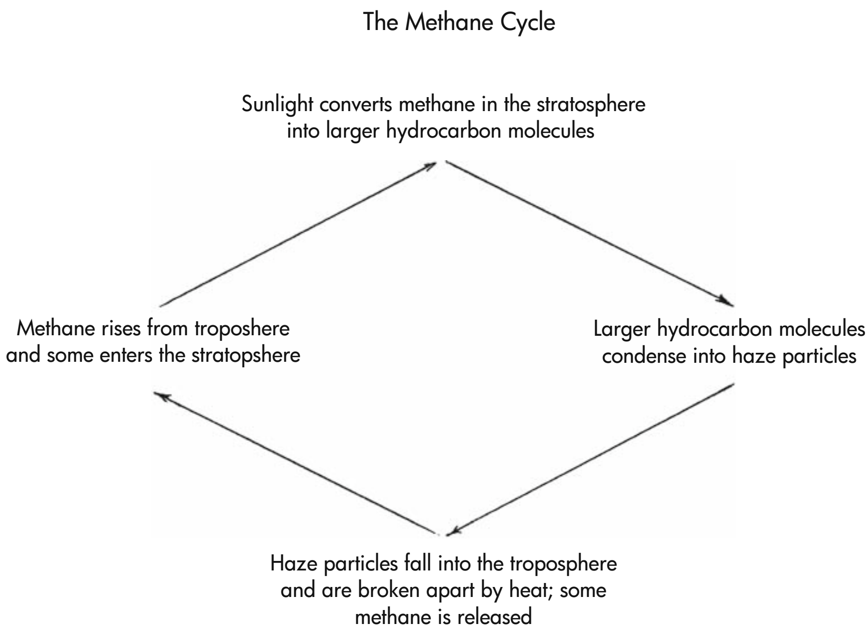

Figure 1.4. The methane cycle on Uranus. Methane in the stratosphere is converted into larger hydrocarbons, which then condense into haze. The haze falls into the troposphere where the temperatures rise to the point where the larger hydrocarbons are broken down into methane. Some of the methane rises to the stratosphere where the process is repeated. (Credit: Richard W. Schmude, Jr.)

charged particles. It is replenished, though, when haze particles fall into the troposphere. When this occurs, the particles are broken apart by heat and methane is released. Some of this methane works its way back up into the stratosphere.

Lower Atmosphere

The lower atmosphere includes the troposphere, which lies below the tropopause – the coldest part of the atmosphere. Figure 1.5 shows the different cloud and haze layers that may be present in the middle and lower atmosphere. When one looks at Uranus through a telescope, he or she sees the troposphere. The atmosphere down to ~1 bar is usually transparent in visible light. The troposphere at around the 1.0 bar level contains ~83% hydrogen, ~15% helium and 1–2% methane (by volume). The methane concentration rises with increasing depth below the 1.0 bar level. Figure 1.6 shows a nearly true color image of Uranus when Voyager 2 was on the dark side of the planet.

Uranus did not produce much internal heat in 1986, and, as a result, there probably was not much convection in the lower atmosphere. This lack of convection may have led to the absence of ammonia and other compounds at the 1–3 bar level. This, in turn, may have affected the types of hazes and clouds that developed there.

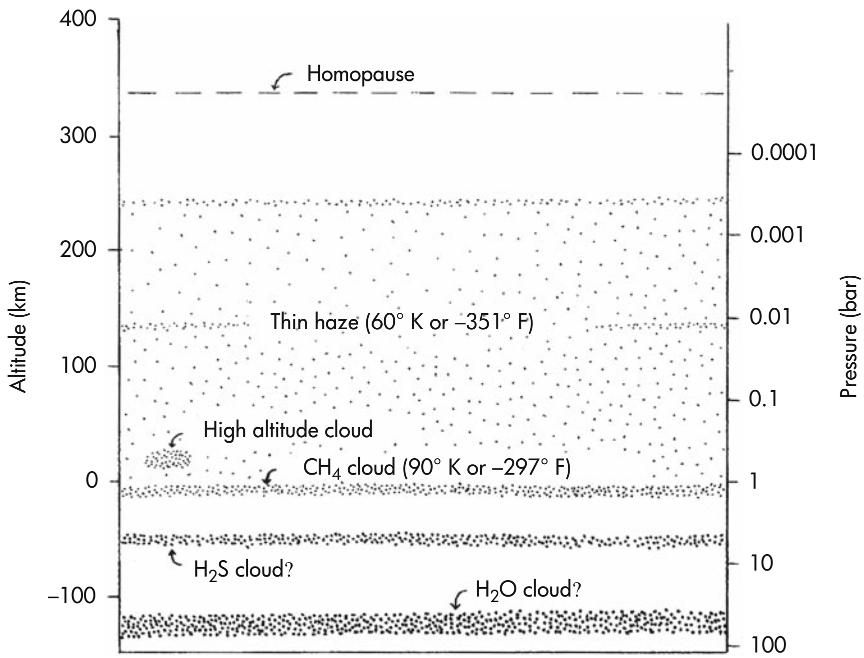

Figure 1.5. A diagram showing how Uranus's middle and lower atmosphere may appear. The altitudes are with respect to the 1.0 bar level. Different levels of pressure are shown at the right. (Credit: Richard W. Schmude, Jr.)

Figure 1.6. A Voyager 2 color image of Uranus and its dark side: This image was taken through three different color filters and was recombined to produce this image. (Credit: Courtesy NASA/JPL-Caltech.)

Chemical reactions may be another reason for the lack of different compounds at the 1–3 bar level. One gas, carbon monoxide (CO), if present, would be converted quickly into methane through the reaction:

$$CO(g) + 3H_2(g) \longrightarrow CH_4(g) + H_2O(g) \tag{1.1.}$$

The (g) represents the gas phase. The low amount of ammonia (NH_3) may be due to the reaction:

$$NH_3(g) + H_2S(g) \longrightarrow NH_4SH(s) \tag{1.2}$$

where the (s) in reaction 1.2 means the solid phase.

Clouds

Before we discuss clouds on Uranus, let's review how clouds form and how one estimates cloud altitudes.

What is a cloud? On Earth, most clouds are made up of millions of either microscopic liquid water droplets or microscopic ice particles. Microscopic particles undoubtedly make up the clouds on the other planets as well.

Clouds on Earth form when the relative humidity exceeds 100% and when microscopic solid particles are present where gases can condense. The relative humidity (RH) is defined as:

$$RH = (AC/MC) \times 100\% \tag{1.3}$$

where "AC" is the actual amount of gaseous water in the air and "MC" is the maximum amount of gaseous water that the air can hold. Hot air can hold more gaseous water than cold air, so MC drops as the temperature drops. Oftentimes, air will contain lots of gaseous water and, when it cools, it causes the RH to reach 100%; at this point, some of the gaseous water condenses into microscopic droplets, forming clouds.

The situation is similar for Uranus, except that one is dealing with methane instead of water in the upper troposphere. The atmosphere can hold only a specific amount of gaseous methane. When it cannot hold any more, the methane either condenses into a cloud if condensation nuclei are present, or becomes a super-cooled vapor if no nuclei are present.

Astronomers use different wavelengths to estimate cloud altitudes. Let me explain how this works. Essentially, light is absorbed and scattered by the gases in Uranus's atmosphere. At pressures greater than ~0.1 bar, hydrogen and helium begin absorbing visible and near-infrared light. Methane also absorbs light. These gases absorb some wavelengths more than others and, as a result, different wavelengths of light sample different depths in Uranus's atmosphere. One example is that infrared light having a wavelength of 1.665 μm reaches the ~1.0 bar level, whereas 2.12 μm light only reaches down to the ~0.3 bar level. Therefore, if a bright cloud is imaged with 1.665 μm light, but not 2.12 μm light, it probably lies between the 0.3 bar and 1.0 bar levels. Essentially, this cloud lies below the 0.3 bar level because it did not show up in 2.12 μm light; however, it lies above the 1.0 bar level because it did show up in 1.665 μm light. In many cases, clouds at a specific altitude will affect one type of light but not another type, due to absorption by the overlying atmosphere. Therefore, images made with different types of light probe different depths in Uranus's atmosphere.

We can learn about the altitudes of the different clouds from multi-wavelength studies. When a high-altitude cloud is imaged, what is really happening is that either a low-lying cloud has developed a high-altitude top where the light is reflected, or light is reflected by a high-altitude cloud. In either case, more light is reflected by the cloud than the surrounding areas and, as a result, it is bright. In Figure 1.7, the low-altitude cloud reflects little visible light because the overlying gas layer absorbs it. The high-altitude cloud, however, reflects more light.

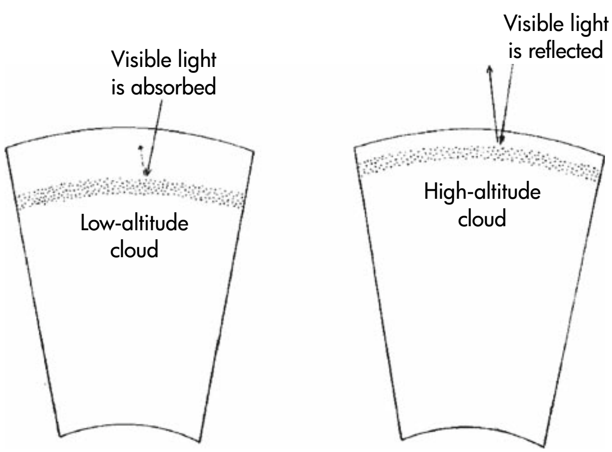

Figure 1.7. High-altitude clouds (right) reflect visible light before it is absorbed by the deeper layers of Uranus's atmosphere. Low-altitude clouds (left), on the other hand, do not reflect as much visible light because it has to pass through a thicker portion of the atmosphere; hence, more of it is absorbed. As a result, high-altitude clouds are brighter than low-altitude clouds in this example. (Credit: Richard W. Schmude, Jr.)

We are not sure of the cloud layers in Uranus's atmosphere. Either a thin methane cloud layer or scattered methane clouds may lie near the one to two bar level. This cloud may change with Uranus's seasons. Temperatures at this level are close to those at which methane condenses. A second and thicker cloud layer may lie near the four bar level. We can only speculate on the chemical composition of this cloud; it may be composed of hydrogen sulfide (H_2S) or ammonia (NH_3). Many astronomers believe that a third cloud layer is at a depth of several tens of bars. Uranus's microwave and radio emissions are consistent with a deep cloud layer.

One recent study is consistent with a haze extending down to several bar, without a methane cloud layer near the one to two bar level. This study is evidence that we still have a lot to learn about Uranus's atmosphere, but that progress is being made!

Astronomers report that the intensity of radio waves at a wavelength of 3.5 cm underwent a cyclic change between 1966 and 2005. The intensity reached a maximum in the mid-1980 s. One interpretation of this data is that the radio waves originate in Uranus's interior and that the atmospheric opacity to radio waves changes between Uranus's south pole and equator. This change may be due to a difference in the opacity of the deep $\sim$50 bar cloud layer between polar and equatorial latitudes.

On Earth, several changes in our atmosphere occur such as cloud formation, cloud dissipation, lightening and precipitation. Most or all of these same processes occur now on Uranus. The Voyager 2 probe detected bursts of radio waves which are probably lightning bolts. We are not sure which cloud layer is producing the lightning. No lightning flashes from Uranus were imaged by Voyager 2. Recent studies have shown that clouds on that planet spring up and dissipate. Some clouds can change in as little as an hour, while others can last more than a month. We are not sure if rain occurs on Uranus. Small amounts of haze may fall to lower altitudes. The deep layers of Uranus's atmosphere may produce methane rain.

Starting in the 1980 s, scientists began studying the movement of clouds on Uranus. Cloud movement shows the wind speed. Cloud movement faster than the planet's rotation period of 17.24 hours is prograde movement, and the wind speed is positive; otherwise, the movement is retrograde with a negative speed. Clouds that rotate once every 17.24 hours have a speed of 0 m/s. Wind speeds on Uranus change with latitude. Winds near the equator move slower than those at around 40°N or S and this causes clouds to rotate at different rates. See Figure 1.8. This also occurs on Neptune, but it is different from Jupiter and Saturn, where the winds near the equator are almost always faster than those at around 40°N or S. We are not sure why equatorial winds on Uranus are so slow.

The highest wind speed measured for Uranus is 218 m/s (488 miles/hour). This is higher than Jupiter's maximum wind speed but is less than the corresponding speed on Saturn. There is a chance that the winds on Uranus change. One group reports that the winds between 20°N and 40°N accelerated between the late 1990 s and 2003.

Astronomers have used visible and near-infrared light to image Uranus's clouds. We cannot see near-infrared light, but electronic cameras can detect it. Most clouds imaged from Earth-based telescopes appear to be 1,000–2,000 km across. We are not sure whether each cloud is a single feature or is a group of smaller clouds.

Thanks to the quality of the Keck and Hubble Space Telescopes, astronomers are now beginning to understand a few statistics of cloud development on Uranus. Two groups of astronomers imaged several dozen clouds on Uranus in 2003 and

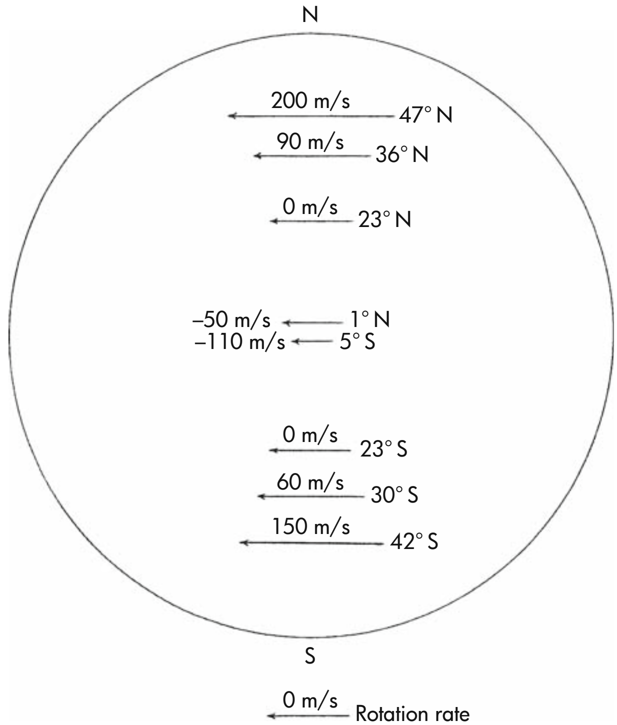

Figure 1.8. Different latitudes of Uranus rotate at different speeds. The large circle is Uranus and the length of the arrow is proportional to the rotation speed. If the wind speed is positive, the wind is prograde; otherwise it is retrograde. Features moving with prograde winds rotate faster than Uranus's rotation rate of 17.24 hours; otherwise they rotate slower. In this figure, the winds at 47°N, 36°N, 30°S and 42°S are prograde whereas those at 1°N and 5°S are retrograde. (Credit: Richard W. Schmude, Jr.)

2004. Most of the clouds were restricted to two areas; 20°S to 50°S (28% of clouds) and 0°N to 50°N (68% of cloud features). The northern hemisphere had more than twice the number of clouds as the southern hemisphere. These clouds were visible in J filter and H filter images. Is this distribution dependent on the season, or is it fixed? Only further observations will answer this question.

One high-altitude cloud developed in July 2004 near 36°S. We know that the cloud had a high altitude because it was bright in 2.12 μm light, which only probes layers above about 0.3 bar. Other bright clouds were not visible in this filter because they were at altitudes below the 0.3 bar level. The discovery of this cloud led one astronomer to state that Uranus has gone from "boring and unchanging" to "interesting and variable". This cloud is interesting because of its high altitude.

Cyclic Changes

There are two cyclic changes of sunlight on Uranus – diurnal and seasonal. Diurnal changes occur as a result of rotation. Diurnal changes are minimal when the poles are nearly facing the Sun, as was the case in 1986. When Uranus is near an equinox point, the situation is different – all areas receive some sunlight during each rotation and, hence, may experience temperature changes. Temperature changes may affect cloud development, so it is important to understand these changes and their magnitude at different atmospheric altitudes.

The changing amounts of sunlight will not affect all parts of Uranus's atmosphere in the same way. Some parts receive lots of sunlight when the Sun lies overhead and, as a result, these areas warm up quickly. Deeper layers, say below the four bar level, will not receive much sunlight even when the Sun is directly overhead; hence, these layers will not warm up at the same rate as the higher altitude areas. There is a good chance that diurnal and seasonal temperature changes are smaller for deep layers compared to ones higher up.

One astronomer at Lowell Observatory carried out a series of measurements in April 1975 and was unable to detect any periodic brightness change exceeding 0.005 magnitudes due to rotation. He used the Stromgren b and y filters. One ALPO member carried out similar studies in August and September 2001 and October 2006 with the broadband V filter. He also detected no diurnal brightness change that exceeded 0.02 magnitudes. These results show that all longitudes of that planet had nearly the same brightness in visible light when they faced the Sun during the times of observation.

A UK amateur astronomer carried out a series of brightness measurements on six nights close to opposition in September 2007. He used filters that were transformed to the Johnson V and cousins Ic system. His results are consistent with a small diurnal brightness changes amounting to a little over one percent in the Ic filter with a period close to that of Uranus's magnetic field. The diurnal brightness change in the V filter, if present, is only a small fraction of one percent.

Does Uranus undergo seasonal changes even though its axis lies close to the ecliptic plane? Yes; in fact, during one 84-year revolution its polar regions receive more sunlight than the equatorial regions. Each of the seasons on Uranus is about 21 years long. The long winters mean that some parts of the atmosphere receive no sunlight for many years, and, as a result, this may affect the atmospheric dynamics. At the time of this writing, we are beginning to see several trends that may be due either to the seasonal cycle of sunlight or to the cycle of changing viewing geometry. Between 1985 and 2007, Uranus's southern hemisphere experienced summer while the northern hemisphere experienced winter. [The International Astronomical Union (IAU) convention is used here.] Starting in late 2007, the southern hemisphere started experiencing fall and the northern hemisphere started experiencing spring; and, for the first time in over 40 years, sunlight fell on Uranus's north pole.

Figure 1.9 shows a recent Hubble Space Telescope image of Uranus and some of its cloud belts. The image was made with three different near-infrared filters, and it shows a bright south polar region. The small white dot is the moon Ariel, and the dark circle is the shadow cast by that moon. Satellite transits will not have much of an effect on the brightness of Uranus.

Peak temperatures may not correspond to high amounts of sunlight on Uranus. One group predicts the highest polar temperatures at the 540 mbar level occur at equinox, which is not the time of maximum solar insulation. They predict that seasonal temperatures lag behind solar insulation by about a quarter of a Uranian year. The temperatures near Uranus's south pole are predicted to rise from 58 K (near spring equinox – 1968) to 60 K (near autumn equinox – 2005) at the 540 mbar level.

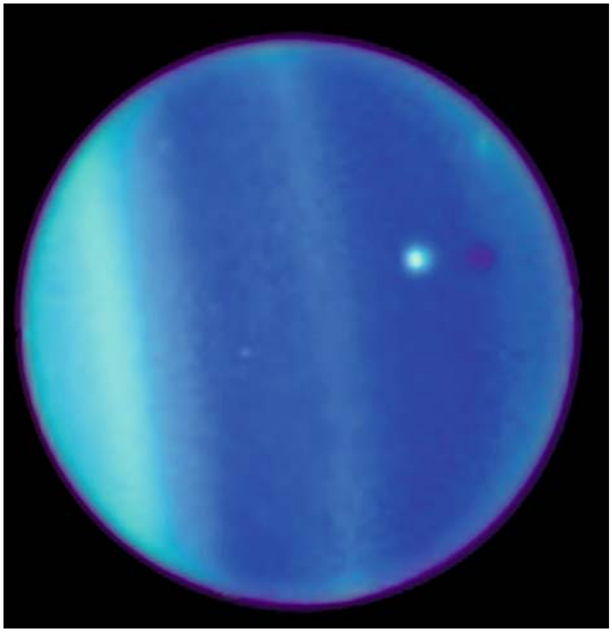

Figure 1.9. A false color image of Uranus made from three different near-infrared images. The bright area at the left is the south polar cap. The bright circular spot is the moon Ariel and the dark spot is Ariel's shadow. (Credit: NASA, ESA, Larry Sromovsky, Heidi Hammel and Kathy Rages.)

Long-Term Brightness Changes

During the last half century, Uranus has undergone a cyclic change in brightness that may be related to its seasons. Seasonal changes in either temperature or viewing geometry may affect the brightness of Uranus. In fact, one astronomer published a paper describing long-term brightness changes over 70 years ago. When the polar areas faced the Sun and Earth during solstice, Uranus was usually brighter than when its equator faced us. This is shown in Table 1.4. More recently, people have measured the brightness of Uranus with electronic equipment. One

Table 1.4. Seasonal brightness changes observed from visual magnitude estimates

Year	Seasonal time	V_o (vis)[a]
1882	Equinox	5.7
1901	Solstice	5.4
1923	Equinox	5.7
1946	Solstice	?
1966	Equinox	(5.2)
1985	Solstice	5.6
2006	Near Equinox	5.7

[a] This symbol is for the human eye which has a different sensitivity than the V filter.

group reports that Uranus gradually dimmed near the 1966 and 2007 equinoxes but brightened near the 1985 solstice. The brightness changes from one year to the next were gradual, but, over several years, they were substantial.

Lowell observatory astronomers measured a brightness drop of 0.03 and 0.10 magnitudes for Stromgren b and y filters between 1985 and 2004. Using a filter transformed to the Johnson V system, members of the Association of Lunar and Planetary Observers (ALPO) measured a 0.06 magnitude drop between 1991 and 2006. See Figure 1.10. All measurements in the figure were normalized to average V(1,0) values. This normalization procedure is discussed further in Chapter 5. The Lowell and ALPO results are consistent with Uranus undergoing a brightness change of $\sim$0.1 magnitudes in several visible wavelengths between its 1985 solstice and its equinox in 2007. The corresponding brightness change in the Stromgren b filter is less than half of what it is in the Stromgren y filter. Members of the ALPO used filters transformed to the Johnson B and V system and report that Uranus did not dim as much in the B filter as in the V filter. They have also measured large brightness drops in filters transformed to Johnson red (wavelength = 0.70 μm) and infrared (wavelength = 0.86 μm) system between 1993 and 2006: a change of over 0.2 magnitudes. The B, V, and R filter data are consistent with the planet undergoing a seasonal color change. Uranus was redder near its 1985 solstice than near its equinox in 2006. The photometric data, therefore, show that the planet undergoes both a color change and a brightness change which matches its seasons. Digital images have shown that the Uranian polar regions have a different color and albedo (the fraction of light that a surface reflects) than areas near the equator.

What is causing the long-term brightness change on Uranus in visible light? There may be as many as three factors at work. First, a small amount ($\sim$0.025 magnitudes) of this change in visible and near-infrared light is caused by the ellipticity of Uranus. Essentially, we see more of Uranus when one of its polar regions faces us than when the equator faces us. This is described further in Chapter 5. Second, the seasonal development and dissipation of clouds may contribute to brightness changes. Finally, we know that the planet becomes dimmer as a result of the movement away of its brighter south polar region. The south polar region is brighter than the temperate and equatorial regions, perhaps because it has a thicker methane cloud layer. This may contribute also to

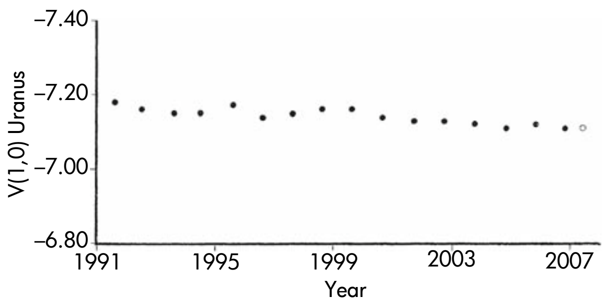

Figure 1.10. The normalized magnitude of Uranus, V(1,0), plotted for different years. All data were collected by members of the Association of Lunar and Planetary Observers (ALPO) using a filter transformed to the Johnson V system. The open circle is one measurement made in 2007 and the filled circles are yearly averages. (Credit: Richard W. Schmude, Jr.)

brightness changes. Perhaps the seasonal development of clouds along with albedo differences between polar and equatorial regions play a role in Uranus's seasonal brightness changes.

One possible scenario for the changes in both visible and radio wavelengths is the two-cloud model shown in Figure 1.11. This model can explain both the seasonal changes in visible light just discussed, and the larger amount of radio waves given off by Uranus when it was at solstice, which was described earlier. In this model, Uranus has two cloud layers, the lower layer at the ~50 bar level blocks radio waves with a wavelength of 3.5 cm coming from the interior, but the upper layer does not affect these waves. An upper cloud or haze layer scatters visible light, but the lower cloud layer does not affect this light. The deep cloud layer is

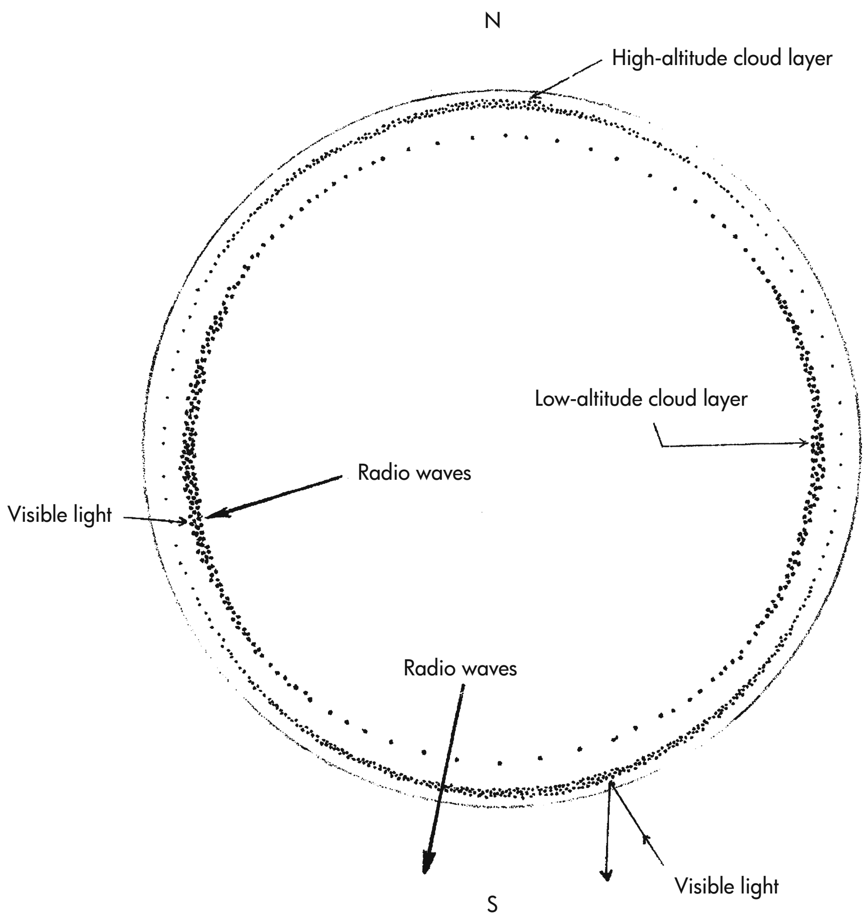

Figure 1.11. A two-cloud layer model of Uranus. In this model, the low altitude cloud layer absorbs radio waves coming from the interior. It is thickest near the equator and is thinnest near the poles. This could explain the low emission when Uranus's equator faced us in 1966 and 2005, and the high emission when that planet's south polar region faced us in 1985. The higher altitude cloud layer reflects visible light, but does not absorb radio waves. If it is highest and thickest near the poles, it could explain the larger amount of visible light reflected by Uranus when its polar region faced the Earth. (Credit: Richard W. Schmude, Jr.)