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Saturn and How to Observe It

With 96 Figures, 86 in Full Color

Springer

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This book is dedicated to my father and mother, Julius and Susan Benton, who gave me my first telescope, to my aunt, Mary Ann Jones, who always encouraged my explorations of the heavens, to my family for their patience and understanding as my astronomical endeavors consumed countless hours all these years, to my mentor and longtime friend Walter Haas, and with deepest gratitude to Saturn observers everywhere who faithfully contributed observations to the A.L.P.O. Saturn Section during my tenure as Section Coordinator.

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Introduction

I received my first telescope, a 60 mm (2.4 in) Unitron refractor, as a surprise Christmas gift from my father when I was 10 years old, and over the next several years, I spent countless hours exploring the heavens, seeking out virtually every celestial object I could find with this small aperture. I consider myself quite fortunate to have been blessed with a dark, unobstructed observing site for most of my childhood, unlike many of my astronomical friends who were always trying to get to a remote location away from city lights to do worthwhile deep-sky observing. I only had to carry my telescope and star charts just a few feet away into my backyard.

By the time I entered high school, the night sky had become a delightfully familiar place. I had tracked down virtually all of the galaxies, nebulae, and star clusters within reach of my little instrument, and I split most of the double stars that were theoretically possible with its exquisite optics. Eventually, I earned sufficient funds working part-time jobs (and saving school lunch money) to purchase a premium 10.2 cm (4.0 in) refractor, another Unitron that I quickly put through its paces, once again surveying my favorite deep-sky objects. Despite the fact that I could see all of them much better with increased aperture, I soon recognized how virtually changeless they were, so I started expanding my observational pursuits. Taking advantage of the increased resolution of the new refractor, my interests evolved almost exclusively to observing the moon and the brighter planets. The wealth of detail I could see on the moon, Jupiter, and Saturn at 250× thoroughly fascinated me, and countless evenings were occupied watching variations in their appearance. Undeniably, why I ended up being chiefly a planetary observer had more to do with the continually changing aspect of the moon and planets than anything else. Now that I had substantially improved aperture at my disposal, as well as a growing collection of eyepieces and accessories, I naturally wanted to observe the moon and planets more often. I soon realized, however, that one of the drawbacks of a larger instrument is decreased portability. Yet, having to carry my clock-driven telescope from place to place never became much of an issue, except when I wanted to view comets or asteroids, for experience had taught me that lunar and planetary observing did not necessarily require dark skies or even an absolutely clear horizon. Like I had done so many times in the past, all I needed to do was step right outside my door to observe. And so, I routinely followed the moon and most of the brighter planets throughout many wonderful observing seasons. Saturn, though, ultimately became my favorite solar system object, and it was not long before I adopted the practice of making careful drawings and writing down all of my observational notes in a logbook for future reference.

My interest in lunar and planetary astronomy followed me well into my college years. The rather gloomy outlook at the time for potential employment opportunities in astronomy forced me to select a major in physics and the environmental sciences, but I always made sure I was never far away from my telescopes on clear nights! By the time I completed my undergraduate studies, my interest in lunar and planetary astronomy had become a virtual obsession, partially ushered in by the unprecedented events of July 20, 1969, when Apollo 11 touched down on the moon in the Sea of Tranquility. The following year I attended my first astronomical convention, where for the first time I met Walter Haas, the founder and then executive director of the Association of Lunar and Planetary Observers (ALPO). I discussed with him my deep interest in contributing worthwhile lunar and planetary observations, and his enthusiasm, encouragement, and guidance helped stimulate my involvement in many ALPO activities. For a few more years, however, the rigors of graduate school occupied much of my available time as I pursued advanced degrees, but I still somehow managed to set aside a few hours a week to spend time at my telescopes recording observations systematically.

The congenial, informal atmosphere of the ALPO proved to be refreshing and wonderfully captivating, and I soon developed a real appreciation for the great diversity of backgrounds and experience of the people I met and corresponded with. Sharing many different philosophical and scientific viewpoints about instrumentation and observing proved to be very meaningful over the years. Although I often found serious observing endeavors to be challenging work, they were also enormous fun. I enthusiastically welcomed the opportunity to contribute all of my own observations to a collective pool of data that had the potential for enhancing our knowledge about Saturn and the solar system as a whole. Through an active exchange of information and ideas in a collective forum, many individuals improved as observers, including myself, and some even went on to become professional astronomers. In addition, I had not been a member of the ALPO for very long before I discovered that the *The Strolling Astronomer* (also known as the *Journal of the Association of Lunar and Planetary Observers*) was essential reading. Most of the information contained within its pages seldom existed elsewhere, and this publication for many years has helped establish and preserve a vital link between the amateur and professional astronomical communities that might not otherwise exist. Annual conventions, often held jointly with other national and international groups, were always enjoyable events as much as they proved to be intellectually stimulating. I can attribute many lasting friendships to such meetings.

In 1971 I was appointed coordinator of the ALPO Saturn Section. I was truly honored to be selected to serve in such a role, and I valued the confidence placed in me by my mentor, Walter Haas, and other ALPO colleagues. Any small contribution that I have been able to make to what we know about the planet Saturn from the standpoint of observational astronomy has come as a sincere labor of love, something I have never grown tired of even after nearly 34 years of recording, analyzing, and publishing detailed apparition reports. But whatever success the ALPO Saturn Section has achieved, none of it would have been possible without the enthusiasm and perseverance of many dedicated observers too numerous to mention here.

Like many of my contemporaries, I consider myself very fortunate to have grown up during the Space Age, witnessing firsthand the enormous revelations and progress made in planetary science. It has been fascinating to watch the marvelous transformation of our nearest celestial neighbors from virtually unknown and inaccessible objects into much more familiar worlds over little more than three decades. With such rapidly occurring advances, I suppose it may be tempting to conclude that the work of amateur astronomers long ago passed into obsolescence from our fixed and limited vantage point in space. And, yes, it is obvious that lunar explorations by the Apollo astronauts or the close surveillance of planets and satellites by orbiting, impacting, or roving spacecraft are clearly beyond the domain of the Earth-based amateur astronomer. But make no mistake about it: there are still many areas of lunar and planetary observation where the work of amateur astronomers has not been outmoded by the onslaught of prohibitively expensive and imposing equipment. Unlike many of their professional counterparts, amateur astronomers continue to enjoy the virtual freedom and advantage of being able to study their favorite solar system objects for extended periods of time and precisely when they want to. Indeed, the greatest potential visual observers have for making useful contributions to science is a systematic, long-term, and simultaneous monitoring of the moon and planets at wavelengths of light to which the eye has greatest sensitivity. An enduring advantage that trained eyes of skilled amateurs have is the unique ability to perceive, at intermittent moments of exceptional seeing, subtle detail on the surfaces and in the atmospheres of solar system bodies that frequently escapes normal photography with considerably larger apertures. And while being careful not to abandon fundamentally important systematic visual work, more and more observers are employing sophisticated electronic devices such as charged couple devices (CCDs), specialized video cameras, and webcams to record impressive, detailed images of the planet, far surpassing what had been previously possible by astrophotography. Furthermore, well-organized systematic work by dedicated amateurs has increasingly caught the attention of the professional community, evidenced by several invitations extended to them for participation in specialized research projects. Simultaneous observing programs and close professional–amateur alliances have already carried over into the 21st century and will undoubtedly grow in the coming years.

If we considered the planet only as a globe, Saturn would be a somewhat smaller, dimmer, and relatively quiescent replica of the giant Jupiter. But, with its broad symmetrical rings, Saturn is an object of exquisite and unsurpassed beauty, holding a particular magnetism for the visual and photographic observer alike. Aside from its obvious aesthetic qualities, the planet exhibits numerous features requiring persistent and meticulous observation, plus eight satellites that are readily accessible to moderate-size telescopes if observers know where to look. In this book, the reader will learn about how to observe Saturn, its rings, and brighter moons using methods, techniques, instruments, and accessories that are readily available to amateur astronomers. One of the major objectives I hope to accomplish is to first acquaint the reader with some fundamental, up-to-date information about Saturn as a planet, then focus on the basics involved in recording useful data and reporting observational results, plus offer suggestions for more advanced and specialized work. Observers will discover how they can take part in well-organized Saturn research programs conducted by international organizations such as the ALPO or the British Astronomical Association (BAA), which share data with the professional community regularly and publish detailed observational reports. As readers utilize the methods and techniques described in this book, the need for even more comprehensive information on certain endeavors will undoubtedly arise. Accordingly, I will always be delighted to correspond with interested parties and provide guidance and advice, including recommendations for more in-depth observational pursuits. For added convenience, the two Internet links—ALPO official Web site: http://www.lpl.arizona.edu/alpo; and ALPO eGroup: Saturn-ALPO@yahoogroups.com—are international sites that readers can visit to access (and download) observing forms and instructions, ephemerides, special alerts and bulletins, results of recent observations, and a wealth of other timely information about Saturn, including ways to interface with professional astronomers. These sites also have abundant sub-links to a host of other important professional and amateur web sites of interest to the Saturn enthusiast, and observers can participate as they desire in discussion forums and promptly exchange information with one another. In addition to the above web sites, I have provided at the end of this book a fairly comprehensive list of references, including well-known astronomical periodicals and authoritative texts that should help readers learn more about the history of amateur observations, as well as the latest developments in planetary science, in particular our rapidly growing knowledge about Saturn.

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Saturn as a Planet

A Simplified View of the Solar System

In a hypothetical spacecraft looking down from far above our solar system, the luminosity of the sun would totally overwhelm that of the nine planets, all of which shine mostly by reflected light. Even the giant Jupiter would be hopelessly immersed in the solar glare. Consider also the fact that the mass of the sun is over 99.8% of the total mass of the known solar system—in contrast with our own geocentric perspective—which essentially relegates the planets, including Earth, to little more than orbiting debris! Yet, it is notable that the orbital motion of the planets comprises nearly 99% of the angular momentum of the solar system. The sun and planets are quite different, too. The sun is mostly plasma generated by nuclear fusion, while the planets are fundamentally solid rocky bodies composed of silicates, metals, ices, as well as varying amounts of liquid or gaseous constituents.

Of the nine planets that compose our solar system (Fig. 1.1), Mercury and Venus move around the sun in smaller orbits than that of the Earth—thus their classification as inferior (or sometimes "interior") planets. The rest of the planets revolve about the sun along orbits that are external to the Earth's orbit and are referred to as superior planets. In another nomenclature scheme, Mercury, Venus, Earth, and Mars are designated terrestrial planets because of their compositional similarity and relatively slow rotation. They are all mostly rocky and metallic bodies with fairly high bulk density, sporting diameters of 4878 km (Mercury), 12,100 km (Venus), 12,800 km (Earth), and 6878 km (Mars). Terrestrial planetary surfaces exhibit varying numbers of craters caused by meteoritic or cometary impacts since the solar system formed 4.6×10^9 years ago, as well as evidence of tectonic activity, such as faulting and volcanism. Their atmospheres are either for the most part nonexistent or are comparatively thin, made up of variable concentrations of gases like carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O_2). Only two of the terrestrial planets have satellites, Earth and Mars, although our singular moon, with a diameter of 3474 km, is considerably more significant than the diminutive two rocky bodies, Phobos and Deimos, orbiting Mars. The Earth, of course, is unique with its ubiquitous life forms and oceans of liquid H_2O.

The giant planets Jupiter, Saturn, Uranus, and Neptune, with diameters of 143,000 km, 120,600 km, 51,100 km, and 49,500 km, respectively, belong to a different class known as the Jovian planets. They have strong magnetic fields, rotate rapidly, and their compositions are dominated by 75% to 90% hydrogen (H_2) and 10% to 25% helium (He), with varying amounts of water (H_2O), ammonia (NH_3), methane (CH_4), and other trace substances. All four Jovian planets have a rather

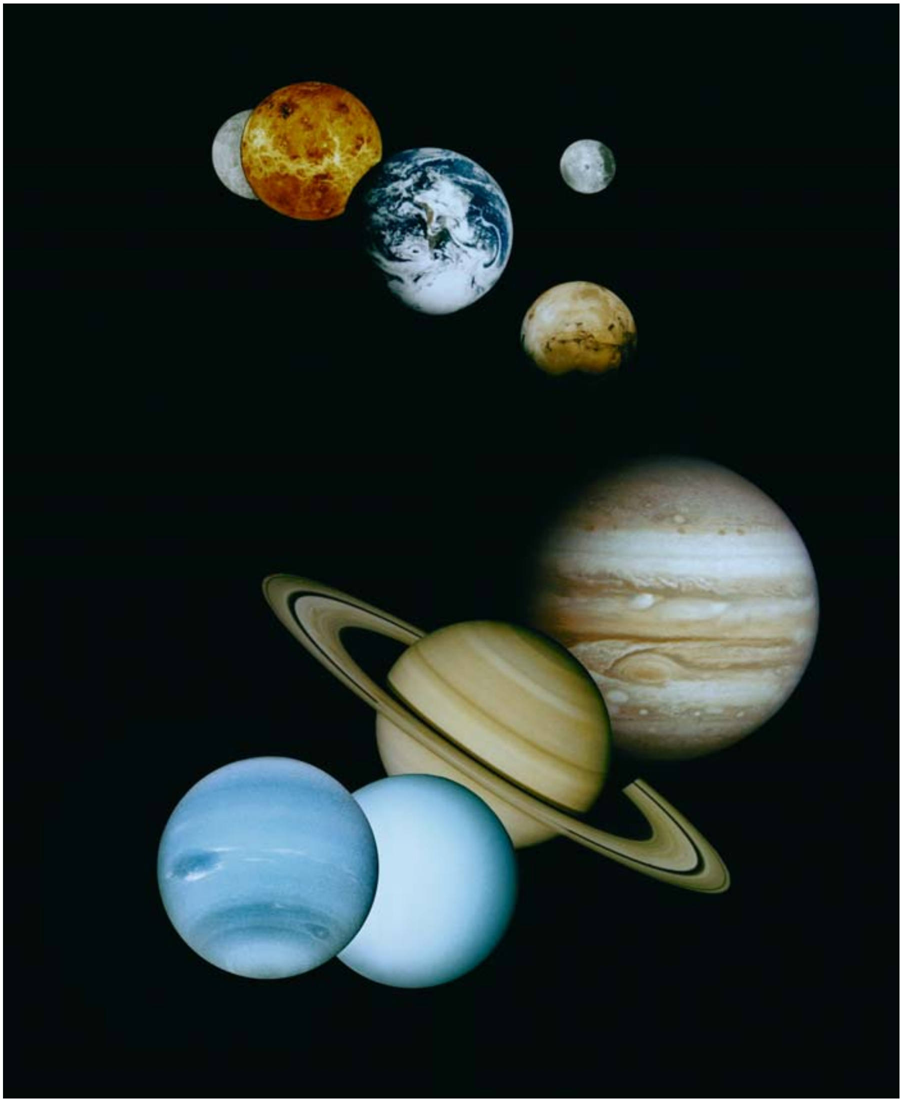

Figure 1.1. In this solar system montage of recent spacecraft images, the terrestrial planets (Mercury, Venus, Earth and its moon, and Mars) are roughly to scale with each other; likewise, the Jovian planets (Jupiter, Saturn, Uranus, and Neptune) are nearly to scale. Pluto does not appear in this assemblage of images. North is at the top in this image. (Credit: NASA and Jet Propulsion Laboratory, Pasadena, California.)

large number of accompanying satellites ranging in size from tiny moonlets, barely a few kilometers across, to exotic worlds, many sporting impact craters of all sizes, ice fields and wrinkled terrain, active volcanoes, and a host of other unique characteristics. A few are even larger than Mercury and our moon, and at least one, Saturn's Titan, has a fairly substantial atmosphere. Another distinguishing attribute of the giant planets is the presence of rings, most of them made up of rocky or icy debris, but none of the other Jovian planets has rings that come even close to rivaling the broad, majestic system that encircles Saturn.

Lastly, there is Pluto with a diameter of 2274 km, which presumably is composed of 70% rocky material and 30% icy substances, accompanied by a satellite Charon that is about half its size. There is a continuing dispute among astronomers as to whether Pluto should truly be considered a planet or demoted and thought of only as one of the larger asteroids or cometary bodies.

In addition to the nine planets and their natural satellites, there are two classes of smaller bodies orbiting the sun, the asteroids and comets, which represent material left over following the formation of the solar system. Most asteroids exist in orbits between Mars and Jupiter, but may also occupy gravitationally stable regions 60° ahead of and 60° behind major planets like Jupiter (e.g., the Trojan asteroids). Asteroids have diameters less than 1000 km, are composed mostly of rocky or metallic substances, and most have roughly circular orbits that generally lie within several degrees of the plane of the solar system. Comets are icy bodies a few kilometers across that can produce gaseous haloes and long wispy tails of considerable size and brightness when they approach the vicinity of the sun. Most comets are situated in the Oört cloud well beyond the major planets, but a few orbit near Neptune in the Kuiper belt, and they can have orbits of varying eccentricity and inclination. When they are far from the sun and very faint, it is sometimes extremely difficult to distinguish a comet from an asteroid.

Saturn: Basic Characteristics and Terminology

With a diameter of 120,600 km, Saturn resides at a mean distance from the sun of 9.54 astronomical units (AU), where 1 AU is equal to 1.43×10^9 km (the Earth's mean heliocentric distance), and completes one orbit in 29.5^y. It has a mean synodic period of 378^d (the time elapsed between one conjunction of Saturn with the sun to the next), so one apparition of the planet lasts slightly longer than one terrestrial year. Saturn's annual eastward motion relative to the background stars is approximately 12°; thus, it can remain in one constellation for quite some time. From perihelion to aphelion, Saturn's distance from the sun varies from 9.01 to 10.07 AU, respectively, which translates into a moderate orbital eccentricity of 0.056. Saturn's orbit is inclined to the ecliptic by 2.5°.

At opposition, Saturn can approach the Earth as close as ~8.0 AU and attain a maximum brightness of –0.3 m_v (where m_v denotes visual magnitude), and it can outshine every star in the sky except Sirius and Canopus. Even so, because of its comparatively large distance from the sun, it is considerably fainter than Jupiter or Mars (when Mars is near opposition), but this is not the only factor that affects the brilliance of Saturn as seen by observers on Earth. Because the majestic ring system is so highly reflective, the brightness of the planet as a whole is substantially controlled by the orientation of the rings to our line of sight. So, at opposition, and when the rings are open to their maximum extent, Saturn is at its brightest. When the rings appear edge-on to us, however, the visual magnitude of the planet may never surpass +0.8 m_v at opposition. Saturn has a Bond albedo, which is the total percentage of sunlight reflected by a planet in all directions, of 0.33. It

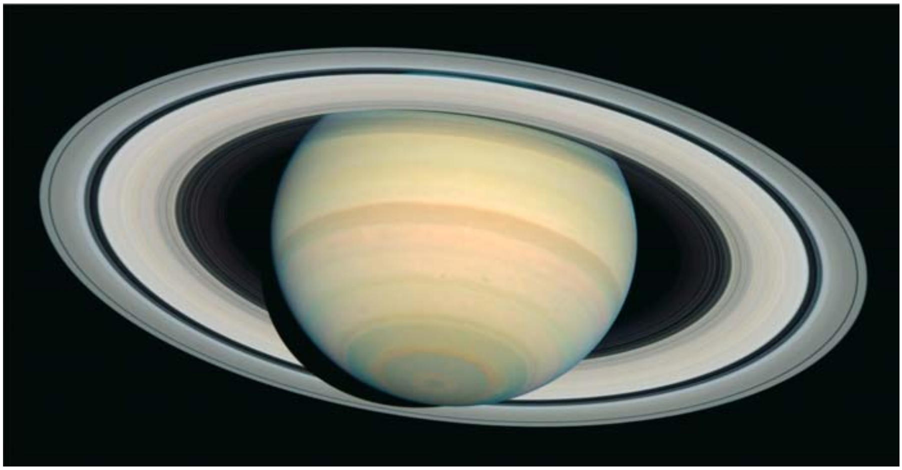

Figure 1.2. Saturn displays its familiar banded structure, with haze and pastel colors of NH_3–CH_4 (ammonia–methane) clouds at various altitudes in this Hubble space telescope (HST) image taken on March 22, 2004. The magnificent rings, seen here near their maximum tilt of 26.7° toward Earth, exhibit subtle hues suggesting chemical differences in their icy composition. North is toward the top in this image. (Credit: NASA, European Space Agency, and Erich Karkoschka, University of Arizona.)

has a visual geometric albedo, *p*, or percentage of sunlight reflected at 0° phase angle (full phase), of 0.47.

The tilt angle between Saturn's axis of rotation and the pole of its orbit, or obliquity, is 26.7° (the Earth has the familiar value of 23.5°). Although the planet's rotational axis maintains roughly the same orientation in space, it is obliquity that causes one hemisphere of Saturn to be tipped toward or away from the sun at certain points in its orbit. So, just like the Earth, Saturn exhibits seasons.

In almost any telescope, Saturn is a magnificent, enchanting object, but this is chiefly because of its best-known feature, the exquisite ring system (Fig. 1.2). In the eyepiece of a moderate-size telescope, the planet has a distinctly yellowish color, and at opposition (when Saturn is opposite the sun in the sky and can be seen virtually all night) the globe may reach a maximum angular equatorial diameter of 19.5″. As Saturn orbits the sun (as seen from the Earth), the most dramatic consequence of the Saturnian seasons is the varying presentation of the rings. Because the ring system is precisely in Saturn's equatorial plane, when the planet's North or South Pole is tipped toward the sun, summer occurs in that hemisphere. During Saturnian summer, the rings reach their maximum opening of 26.7° to the sun and to our vantage point on Earth, and they are at their brightest. Winter occurs in the opposite hemisphere of Saturn, which is tipped away from the sun and Earth, and most of that region is typically hidden from view by the rings as they pass in front of the globe. It is during spring and fall on Saturn that the rings can be oriented edgewise to the sun and to our line of sight, sometimes even disappearing for a period of time, even in a large telescope. These are periods during the Saturnian year when equal portions of the Northern and Southern Hemispheres of the planet become visible in our telescopes. The oblateness of Saturn's globe, or deviation from a perfect sphere because of rotation, is immediately obvious and amounts to 0.108.

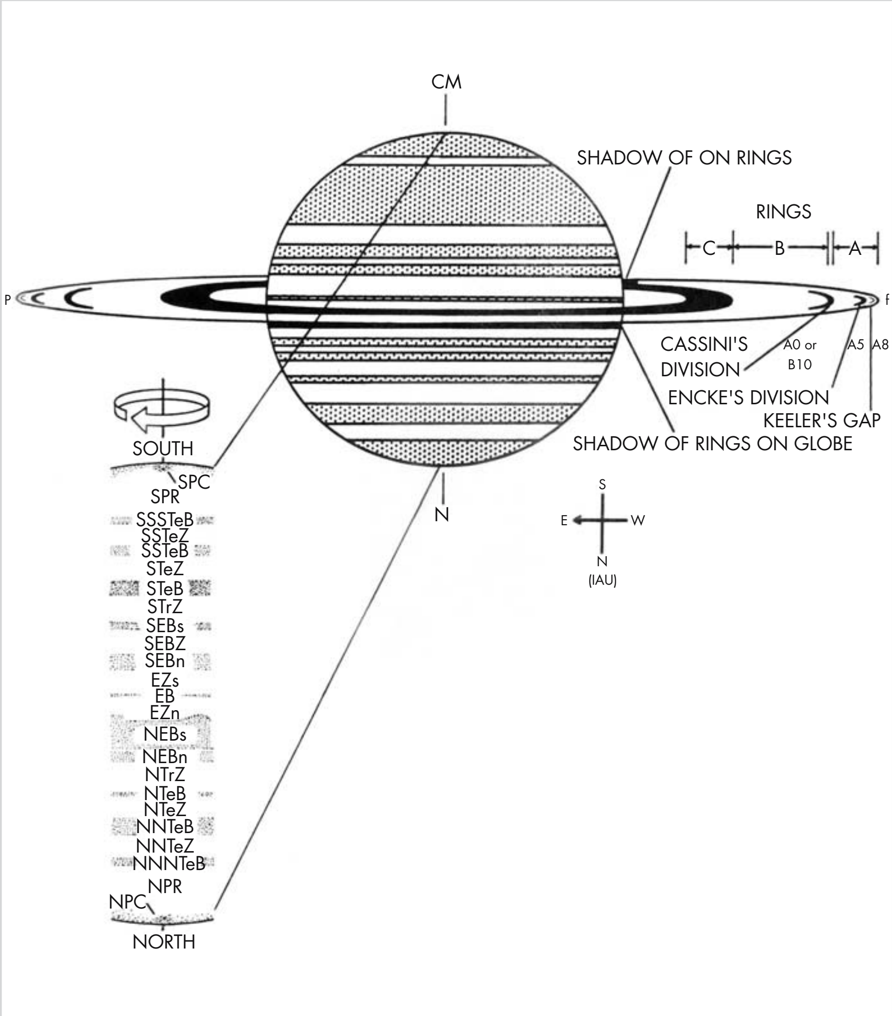

Figure 1.3. Diagram of the major features of Saturn's globe and rings, South is toward the top and east is to the left in this normally inverted view as seen in most astronomical telescopes, and features move across the globe from right to left (west to east) in the International Astronomical Union (IAU) convention. (Credit: Julius L. Benton, Jr., ALPO Saturn Section.)

Similar to Jupiter, Saturn displays a series of dark-yellowish to tan cloud belts and white to pale-yellowish zones extending across the globe roughly parallel to the equator and plane of the ring system. On occasion, discrete detail is visible in the belts and zones on the globe of Saturn. Any features seen on the planet may be similar in form to those on Jupiter, but a greater depth of overlying haze makes them poorly visible most of the time. Projections or appendages from belts, sometimes leading into extended dusky festoons, or bright spots in the zones, comprise the most frequently recorded types of phenomena. Figure 1.3 is a diagram of Saturn's globe and rings (as seen in a typical inverting astronomical telescope) with the major atmospheric features and ring components that are sometimes

Table 1.1. Nomenclature and characteristics of major saturnian global features*

Feature	Description	Notes
SPR	South polar region	This is usually the most southerly part of the globe, sometimes differentiated into a SPC (south polar cap) in the extreme south. The SPR is usually quite variable in appearance, usually quite dusky but can be bright on occasion.
SSTeZ	South south temperate zone	This zone typically separates the SSTeB and the SPR; it is usually much duller than the other southern hemisphere zones.
SSTeB	South south temperate belt	Infrequently visible, but even when seen, it is a very thin, ill-defined feature.
STeZ	South temperate zone	This zone is usually quite bright, sometimes showing faint wispy dark features and occasional bright spots at the threshold of vision.
STeB	South temperate belt	This belt is usually visible, and it has occasionally displayed some poorly defined dark spots.
STrZ	South tropical zone	Like the STeZ, this zone is also quite bright, and it periodically may exhibit dusky phenomena and small, diffuse bright spots or regions.
SEB	South equatorial belt	This belt is often quite dark, easily seen, and usually is differentiated into the SEBs and SEBn (southern and northern components, respectively), separated by a brighter SEBZ (south equatorial belt zone). The SEB frequently displays more activity than do the other belts in the southern hemisphere of Saturn's globe.
EZ	Equatorial zone	Almost without exception, the EZ is the brightest zone on the planet's globe, and dusky details and white spots have been observed in this zone with a greater frequency than in other global regions. The very thin and rarely seen EB (equatorial belt) separates the EZ into the EZs and EZn (southern and northern components, respectively).
NEB	North equatorial belt	Exhibits many of the same characteristics of its counterpart in the southern hemisphere of Saturn, the SEB, including differentiation into an NEBs, NEBn, and NEBZ.
NTrZ	North tropical zone	Like the STrZ, this feature lies between two dusky belts and is often quite bright, showing activity occasionally in the form of festoons or whitish mottlings.
NTeB	North temperate belt	Usually visible, this belt has shown activity from time to time in the form of dark spots or disturbances.
NTeZ	North temperate zone	A fairly bright zone, similar in characteristics and periodic activity to the STeZ.
NNTeB	North north temperate belt	Seldom reported, but under optimum circumstances, it may be barely perceptible as a delicate, linear belt crossing the globe.
NNTeZ	North north temperate zone	A somewhat dull zone sometimes seen separating the NNTeB and the NPR.

Table 1.1. Continued

Feature	Description	Notes
NPR	North polar region	This is the northernmost part of the globe, often quite dusky in its overall appearance, but sometimes it can brighten; at the extreme northern limb, a NPC *(north polar cap)* can occasionally be seen.

* Sequence follows that in *Fig. 1.3*; visibility of some global features is affected by the location and orientation of the ring system.

visible. Table 1.1 gives brief details on the nomenclature and some rough (not necessarily typical) characteristics of the main belts and zones of Saturn's globe.

The equatorial regions (NEB, SEB, and EZ; see Table 1.1) have a sidereal rotation period of $10^h14^m00^s$, and this region is designated system I. The remainder of the globe of Saturn is called system II with a sidereal rotation period of $10^h38^m25^s$, although the SPR and NPR are sometimes excluded and assigned a rotation rate that is equal to system I. A system III radio rate of $10^h39^m22^s$ has also been determined for the interior of Saturn. Latitudes of belts and zones on the globe are not appreciably altered by rotation, and as shown in Figure 1.3, features move across the planet from right to left (in the normal inverted view) in a West-to-East, or prograde, fashion. Note that west and east here corresponds to true directions on Saturn as adopted by the International Astronomical Union (IAU), which are opposite normal sky directions when viewing Saturn from Earth, and we will adopt this convention without exception throughout this book. In addition, readers should be aware that the preceding (*p*) limb of Saturn is to the east and the following (*f*) limb is to the west in the IAU sense in the normal inverted view of an astronomical telescope.

By terrestrial standards, Saturn is a giant planet, despite the fact that it is a little less than a third the mass of Jupiter. As determined by interactions of the planet with its family of natural satellites, the mass of Saturn has been determined to be 5.68×10^{26} kg. The mean density of 700 kg/m^3 for Saturn is the lowest of the major planets, and realizing that water (H_2O) has a density of 1000 kg/m^3, Saturn would float on a sufficiently large hypothetical ocean!

Even though Jupiter, Uranus, and Neptune are now among the family of planets known to have rings encircling them, those of Saturn are clearly in a class all by themselves. The Saturnian ring system is considerably brighter and more complex than any of the others throughout the solar system, with an albedo higher than that of the globe. So the rings contribution to the total brilliance of Saturn as a planet is substantial. Across their major axis, the rings have an angular extent of as much as 44.0″. The ring system lies in the equatorial plane of Saturn, so they are inclined by the same obliquity of 26.7°. As Saturn orbits the Sun in 29.5^y (with the planet's axis of rotation maintaining the same orientation in space) the intersection of Earth's orbit and the plane of the ring system occur twice, at intervals of roughly 13.75^y and 15.75^y. The two periods are of unequal duration because of the ellipticity of Saturn's orbit. The orbital intersection points signify times when the rings appear edgewise to our line of sight. In the shorter period, the southern face of the rings and southern hemisphere of the globe of the planet is inclined toward Earth, and Saturn passes through perihelion during this interval; the tilt of the rings, as

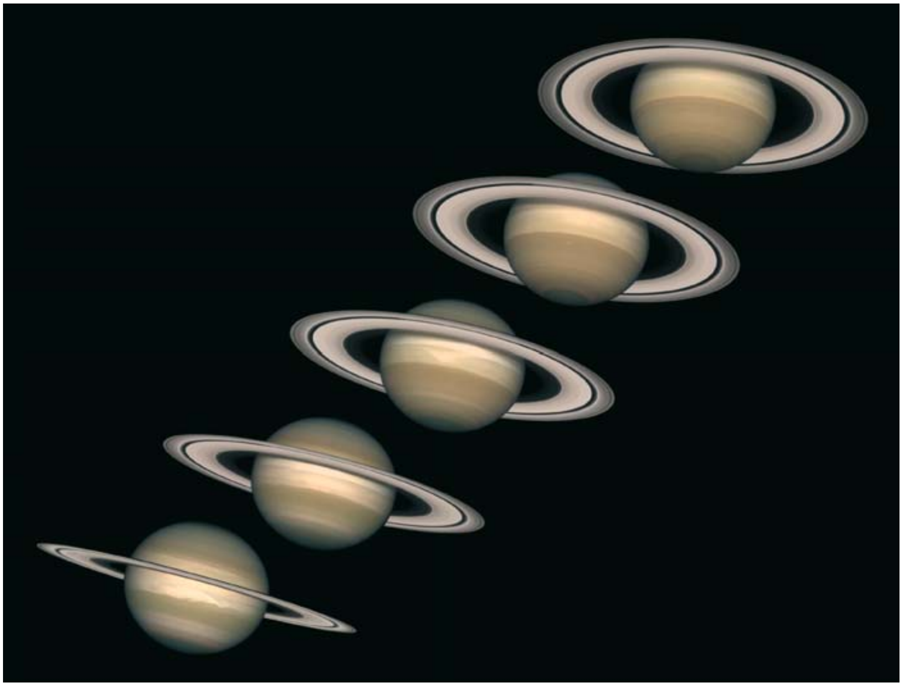

Figure 1.4. These Hubble space telescope images captured from 1996 to 2000 show Saturn's rings open up from just past edge-on to nearly fully open as it moves from autumn towards winter in its northern hemisphere. Saturn's equator is tilted relative to its orbit by 26.7°, very similar to the 23.5° tilt of the Earth. As Saturn moves along its orbit, first one hemisphere and then the other tilts toward the sun. This cyclical change causes seasons on Saturn, just as the changing orientation of Earth's tilt causes seasons on our planet. North is at the top. (Credit: NASA and Hubble space telescope [HST] Heritage Team [STScI/AURA].)

we see them on Earth (as shown in Fig. 1.4), varies from 0° to –26.7° and back to 0° again. In the longer period, Saturn passes through aphelion, and the north face of the rings and the northern hemisphere of the globe are exposed to observers on Earth, and the tilt of the rings to our line of sight changes from 0° to +26.7° and then back to 0°. Because the rings are no more than ~100 m thick, they become extremely hard to see, or they may seem to disappear entirely, when edge-on.

The rings lie inside Saturn's Roche limit, or within the minimum distance from the planet where a body with no appreciable gravitational cohesive forces can exist without disruption. The classical ring system is composed of three major ring components. The first is ring A, the usually seen outermost component with an inner radius from the center of Saturn of 122,200 km, an outer radius of 136,800 km, and a width of 14,600 km. Next is ring B, the central, broader, and brighter ring with an inner radius of 92,000 km, an outer radius of 117,500 km, and a width of 25,500 km. Last is ring C, the dusky inner Crape ring with an inner radius of 74,658 km, an outer radius of 92,000 km, and a width of 17,342 km. Taken together, the classical ring system from tip to tip extends 273,600 km. Rings A and B are separated by a dark gap roughly 4800 km wide, known as Cassini's division. It is visible in small telescopes with good optics and cooperative seeing conditions. About halfway between the inner and outer limits of ring A is Encke's complex with a width of

~320 km, but it is not as well defined as Cassini's gap. About 3200 km from the outer edge of ring A is Keeler's gap, with a width of about 35 km, and although it is visible from Earth, it requires very large apertures to be seen to advantage. All of the aforementioned major ring components and major divisions (including the faint Keeler's gap), which are usually observable from Earth, are illustrated in Figure 1.3.

Ring D, an extremely faint component internal to ring C, has an inner radius of ~67,000 km, an outer radius of 74,510 km, and a width of 7,510 km, and seems to extend downward nearly to the cloud tops of Saturn's atmosphere. Situated just outside ring A is a very narrow ring component, ring F, with an inner radius of 140,210 km, an outer radius of 140,600 km, and a slender width of no more than 390 km or so. Beyond ring F is the extremely tenuous ring G with a radius of 165,800 km, an outer radius of 173,800 km, and a width of 8000 km. Finally, there is the extraordinarily diffuse ring E with an inner radius of 180,000 km, an outer radius of 480,000 km, and a width of 300,000 km, and is the outermost ring component. The rings of Saturn will be discussed in greater detail later, including their interaction with some of the satellites. With perhaps the exception of ring E, it is generally held that these ring components are beyond the reach of the Earth-bound visual observer.

The Atmosphere of Saturn

The composition of Saturn's atmosphere is ~93% hydrogen (H_2) and ~5% helium (He). Minor constituents include methane (CH_4) and ammonia (NH_3), but the greatest percentage of the latter is in liquid or solid form in Saturn's extremely frigid upper atmosphere where temperatures are ~95 K. Traces of water vapor, ethane (C_2H_6), and other compounds occur as well (Table 1.2). Saturn has the lowest mean density of all of the planets at 700 kg/m^3, another indication that the planet has a very H-rich interior with few rocky materials.

Although H_2 and He dominate in the atmosphere of Saturn, accounting for ~98.0% of the gaseous constituents, the amount of He is significantly less than that found in the atmosphere of Jupiter. During Saturn's early history, it is likely that the

Table 1.2. Main constituents of Saturn's atmosphere

Hydrogen	H_2	93%
Helium	He	5%
Methane	CH_4	0.2%
Water vapor	H_2O	0.1%
Ammonia	NH_3	0.02 %
Ethane	C_2H_6	0.0005%
Phosphine	PH_3	0.0001%
Hydrogen sulfide	H_2S	<0.0001%
Methylamine	CH_3NH_2	<0.0001%
Acetylene	C_2H_2	Trace
Hydrogen cyanide	HCN	Trace
Ethylene	C_3H_4	Trace
Carbon monoxide	CO	Trace