THE SATURN SYSTEM

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Saturn is a giant planet surrounded by numerous rings, many satellites, and a large magnetosphere. Although the Saturn system bears a general resemblance to the Jovian system, it has many unique attributes which provide new insight into the formation and evolution of planetary systems. This introductory chapter provides an overview of the results of recent studies of the Saturn system which are described in detail in the following chapters.

Saturn was the most remote planet known to man when it became a unique object of scientific study with the discovery of its rings by Galileo in 1610 (see the chapter by Van Helden). By the 1970s, when the first space probes were launched toward the outer solar system, Saturn was already known to be a giant gaseous planet encircled by three main rings containing centimeter-sized ice-covered particles and surrounded by at least ten satellites. Titan, the largest of these, was known to be a planet-sized body with a substantial atmosphere containing methane, and five others were known to be intermediate-sized icy satellites. It was not yet known, however, whether or not there was a planetary magnetic field with the associated plasmas, trapped particles, and radio emissions.

With the Pioneer and Voyager flybys of Saturn in 1979, 1980, and 1981, the last of the planets visible to the naked eye was visited by spacecraft. As described in the various chapters in this book, these flybys, in conjunction with improved groundbased observations and increasingly sophisticated theoretical analyses, have greatly increased our knowledge and understanding of the Saturn system. In the following sections we briefly summarize those chapters, indicating what is known about the planet, the magnetosphere, the rings, the satellites, and the origin of the Saturn system. Extensive discussions and references will be found in the relevant chapters.

I. THE PLANET

The spacecraft encounters with Saturn altered previous ideas about the significance of apparent similarities between Saturn and Jupiter. These two giants share many characteristics, yet there are basic differences between them that have become more apparent from the detailed scrutiny provided by the spacecraft. Saturn's special qualities seem to be associated with its smaller mass and greater distance from the Sun.

A. The Interior

We encounter these differences as soon as we begin studying models for Saturn's internal structure (see the chapter by Hubbard and Stevenson). Both Saturn and Jupiter are composed predominantly of hydrogen by mass, unlike Uranus and Neptune where compounds of carbon, nitrogen, and oxygen dominate. Yet the heavy-element core of Saturn is proportionately larger than that of Jupiter, and the hydrogen-helium envelope is thinner. On Saturn, the transition from molecular to metallic hydrogen occurs deeper in the envelope than on Jupiter.

The ratio of Saturn's thermal emission and that which it absorbs from the Sun is 1.79 ± 0.10. Although Jupiter has a similar radiation excess, the energy sources probably differ in part. On Saturn, the precipitation of helium in metallic hydrogen is possible, and this process will lead to the liberation of thermal energy through viscous dissipation. This situation arises because Saturn's smaller mass has allowed this planet to cool more rapidly than Jupiter, which is still radiating primordial heat. The review in the chapter by Hubbard and Stevenson suggests that there is also a significant contribution from primordial heat to Saturn's thermal flux.

The rotational period for the conducting region of the core of 10 hr 39 min 24 ± 7 s is derived from observations of Saturn kilometric radiation. The composition and structure of the core are still poorly defined. Models with rock and rock plus ice with various ratios of He/H in the envelope or in a fluid outer core can all satisfy available constraints.

B. The Atmosphere

Composition. The composition of Saturn's atmosphere (see the chapter by Prinn, Larson, Caldwell, and Gautier) offers immediate support to the idea of helium differentiation in the planet's interior. The helium mass fraction is only 0.13 ± 0.04 for Saturn compared with the 0.20 ± 0.04 for Jupiter, which agrees with the solar value. This depletion of helium in the observable envelope of Saturn is consistent with predictions based on the observed thermal flux, assuming the latter is augmented by raining out of helium in the interior. Other elements in Saturn's atmosphere appear to be enriched compared with solar values. The situation is clearest for carbon, since methane, the dominant carbon-containing gas, does not condense. This enrichment in turn suggests a heterogeneous model for Saturn's formation, in which the accretion of a core of $\sim 10\ M_\odot$ is followed by very rapid contraction of the surrounding envelope of nebular gases.

All of the gases found on Saturn are present on Jupiter, but the reverse is not yet true. In particular, the observability of GeH_4 and CO on Jupiter but not on Saturn despite the detection of PH_3 on both planets may imply significant differences in the interiors of these two planets. On the other hand, PH_3 was detected near 10 μm, where there is high signal-to-noise ratio in the infrared spectra, whereas GeH_4 and CO must be observed at 5 μm, where the lower temperature of Saturn makes it much more difficult to observe than on Jupiter. Photochemical models can successfully predict the abundances of nonequilibrium species at higher altitudes, although the vertical distribution of PH_3 remains a problem. A value of $D/H = 2.6^{+3.7}_{-2.0} \times 10^{-5}$ has been derived from Voyager observations of CH_3D. This is similar to the value found on Jupiter, suggesting that this is likely the value of D/H in the primordial solar nebula. This number can thus be used to constrain models for "big-bang" nucleosyntheses.

Cloud Properties. The clouds of Saturn (see the chapter by Tomasko, West, Orton, and Tejfel) are less colorful and form fewer discrete features than on Jupiter. Nevertheless, the Voyager cameras were able to record a variety of cloud systems including a wave-like feature at 46°N, several ovals with white, brown, and reddish colors, and tilted filaments. It is commonly assumed that frozen ammonia is the main constituent of the visible clouds, but an unambiguous spectral identification to support this assumption is still lacking. As for Jupiter, compounds containing sulfur or phosphorus as well as carbon-nitrogen compounds have been invoked to explain the observed coloration. Again there is a lack of spectral signatures. There is an ultraviolet-absorbing layer of small aerosols ($r \sim 0.1$ mm) at high altitudes (pressures $\sim$ 20 mbar) which is particularly prominent over Saturn's poles. These aerosols may have the same composition as a similar layer found on Jupiter, where charged particle precipitation was invoked to explain the association with the poles.

Structure and Dynamics. The thermal structure of Saturn's atmosphere (see the chapter by Ingersoll, Beebe, Conrath, and Hunt) has been studied from a variety of Earth-based and spacecraft observations. It is now possible to define the mean vertical structure with some authority, and to discuss dynamical structures with horizontal scales from 60 to 60,000 km. Motions in Saturn's atmosphere are dominated by the strong, axisymmetric, predominantly eastward zonal flow. Saturn's east-moving equatorial current is twice as broad and four times as fast as Jupiter's. These differences in the currents in the observable cloud layers may be caused by differences in the deep circulation of the atmosphere. In such a model the zonal flow patterns of the cloud motions on both planets may actually extend to great depths, the rotation rate being constant on coaxial cylinders. The dimensions of these cylinders are established by the depth of the molecular envelope in each case.

On the other hand, models for shallow circulation have been proposed that can also account for the observations. Studies of the time-dependent behavior of vortices may prove to be an important diagnostic tool in distinguishing among the various models used to explain the dynamics and in constraining assumptions about flow in the deep interior. At present there are two schools of thought about these vortices: one suggesting they are solitary waves or solitons, the other that they are strongly interactive features called modons. The average eddy velocities on Saturn are less than half as large as those on Jupiter. The planets are further distinguished by the presence of a strong north-south thermal asymmetry in Saturn's upper troposphere, indicating the effect of a seasonal difference in insolation owing to Saturn's higher obliquity (26°7 vs. 3° for Jupiter).

There also appears to be atmospheric lightning as evidenced by Saturn Electrostatic Discharges (SED), which may emanate from the equatorial atmosphere which has a rotation period of 10 hr 10 min (see the chapter by Kaiser, Desch, Kurth, Lecacheux, Genova, Pedersen, and Evans).

C. Upper Atmosphere and Ionosphere

The atmosphere of Saturn appears to be well-mixed up to a level of about 10^{-9} bars (1 nbar), the homopause. The thermosphere and exosphere encompass the region above 10 nbar (see the chapter by Atreya, Waite, Donahue, Nagy, and McConnell). Voyager studies yield an exospheric temperature of 600 to 800 K, some 400 K lower than the comparable temperature on Jupiter. The average temperature of 140 K in the stratosphere and mesosphere is similar to the Jovian value. The vertical transport of species in the upper atmosphere is governed by the eddy mixing coefficient, K. At the homopause on Saturn, $K \sim 10^8$ cm^2 s^{-1}. This is similar to the value derived for Titan, but two orders of magnitude larger than the Jovian value for reasons that are not yet clear.

The Pioneer and Voyager measurements of the peak electron density in Saturn's ionosphere yield values near 10^4 cm $^{-3}$, ten times smaller than the predictions of a variety of theoretical models. A likely explanation of this discrepancy involves a new loss mechanism for H^+ by collisions with vibrationally excited H_2. The primary transfer of energy to the thermosphere appears to be Joule heating caused by the departure of the magnetospheric plasma from corotation with the planet. Unlike Jupiter, the energy from charged particle impact in Saturn's auroral zone does not make a significant contribution to the heating of the thermosphere/exosphere region. Saturn's upper atmosphere thus shares the characteristic of the other regions of the planet in appearing similar but being distinctly different from that of Jupiter.

II. THE MAGNETOSPHERE

The Pioneer 11 encounter in 1979 and the Voyager encounters in 1980 and 1981 revealed a magnetosphere similar to that of the Earth or Jupiter, but with physically significant differences ranging from the unusual symmetry of the Saturnian magnetic field and the sources and sinks of plasma and energetic particles to the generation of kilometric radio waves.

A. Magnetic Field

Saturn has an internal planetary magnetic field (see the chapter by Connerney, Davis, and Chenette) which is confined and distorted by the dynamic pressure of the impinging solar wind, resulting in an extended magnetotail. Saturn's internal dipole moment produces a 0.21 Gauss magnetic field at 1 R_S (60,330 km), similar to that at the Earth's surface. However, the Saturnian magnetic field is unusual in that it is highly axisymmetric with no measureable tilt ($<1°$) between the dipole and rotational axes. There is, however, hemispherical asymmetry due both to a northward offset of 0.04 R_S of the dipole and to higher-order zonal harmonics. Models of the field yield estimates of surface fields of ~ 0.83 Gauss and ~ 0.69 Gauss for the north and south polar regions.

Although the *in situ* observations indicate an axisymmetric magnetic field, observations of periodicities in the burst activity of Saturn's kilometric radiation (SKR) and in the formation of spokes in the B Ring suggest that there may be longitudinal asymmetries closer to the planet. Both phenomena occur preferentially at the same longitude of ~ 115° SLS (Saturn longitude system) with the same periodicity, but at different local times. A local anomaly in the field could not be too localized, however, since the SKR originates in the auroral zone at high latitudes and the spokes occur on mid-latitude magnetic field lines.

In addition to the internal magnetic moment, there is an equatorial ring current of ~ 10^7 A which contributes to the observed magnetic field. The ring current is modeled by an eastward flowing current confined to a 5-R_S-thick ring at distances between ~ 8 and ~ 15 R_S. The total kinetic energy in the ring current is 5×10^{-4} of the magnetic energy in the field beyond Saturn's surface, a ratio similar to that for Jupiter and Earth.

Beyond ~ 15 R_S the subsolar magnetic field is noticeably modified by the presence of the magnetopause current system. For typical solar wind conditions, the nose of the magnetopause is expected to be at ~ 24 R_S. As the dynamic pressure p of the solar wind varies, the location of the magnetopause varies as $p^{1/6}$, similar to the response of the Earth's magnetopause and much stiffer than the $p^{1/3}$ response of the plasma-dominated Jovian magnetodisk.

In the antisolar direction, the magnetotail current system becomes increasingly important beyond ~ 10 R_S, and by 25 R_S the magnetotail diameter is typically 80 R_S and the tail lobe field is ~ 3 nT. The corresponding region of open field lines in the polar region extends down to an auroral zone at latitudes between ~ 75° and ~ 80°.

B. Plasma and Plasma Waves

Several general characteristics of magnetospheric plasma at Saturn resemble those of Jupiter rather than Earth (see the chapter by Scarf, Frank, Gurnett, Lanzerotti, Lazarus, and Sittler). For example, at Saturn the icy satellites and Titan are significant internal sources of plasma which essentially corotates with Saturn, forming an equatorially confined plasma sheet rather than a plasmasphere. However, the rate at which the Saturn sources load mass onto the corotating magnetic field is $\leq 10^{-2}$ of the mass-loading rate provided by Io, so that a plasma-dominated Jovian-like magnetodisk does not form.

The plasma sheet at Saturn consists of at least three distinct regions: an inner plasma torus (≤ 7 R_S), an extended plasma sheet ($7 \leq R \leq 15$ R_S), and a hot outer magnetosphere ($\gtrsim 15$ R_S). There is a systematic increase in electron temperature with radius, ranging from ≤ 1 eV at 4 R_S in the inner plasma torus and increasing to ≥ 500 eV in the hot outer magnetosphere. There is a corresponding increase in the thickness of the disk, with scale heights ranging from 0.2 R_S at the inner edge of the inner plasma torus to ~ 3 R_S in the outer magnetosphere.

Although the exact nature of the sources and sinks of plasma is unresolved, several possibilities have been suggested for the different regions. In the inner plasma torus the abundance of 0^+, and possibly 0^{2+} and 0^{3+}, reaches a maximum between Dione and Tethys, consistent with the icy satellite surfaces being a plasma source. There is an indication that the high-energy tail of the oxygen plasma may extend above 30 keV.

The inner torus region also contains significant plasma-wave activity, the strongest being chorus emission at ≤ 1 kHz. However the amplitudes of the waves are insufficient to cause strong pitch angle diffusion or major precipitation of keV electrons. The prevalent waves are electrostatic electron cyclotron harmonics with frequencies greater than several kilohertz. These emissions occur within the inner torus where the plasma density is high enough so that the plasma frequency is greater than the electron gyrofrequency. These waves may be driven by suprathermal plasma electrons.

The inner plasma torus cannot be the sole source of the extended plasma sheet, since the total plasma content in the torus is smaller than that of the plasma sheet. The inner edge of the extended plasma sheet coincides with that of the cloud of neutral hydrogen which has escaped from Saturn's or Titan's atmosphere. The cloud is ~ 16 R_S thick and extends out to ~ 25 R_S. Ionization of the cloud provides a source of 2×10^{26} H^+ s^{-1} in the region beyond 8 R_S.

The extended plasma sheet also contains heavy ions, although it is not clear whether they are nitrogen or oxygen. Titan would be a likely source for nitrogen, but oxygen would have to originate from the icy satellites, the rings, or Saturn's ionosphere. At least some ionospheric contribution is required by the observation of energetic molecules of H_2 and H_3 in the outer magnetosphere.

In the outer magnetosphere there is considerable variability in plasma density and temperature on short time scales, possibly resulting from the onset of contrifugal instability at the outer edge of the extended plasma sheet and the subsequent outward radial flow of blobs of colder plasma sheet ions and electrons. Titan also sheds a plume of cold nitrogen ions which contributes to the complexity of the outer region. Ionization of the neutral hydrogen cloud can provide the warm hydrogen ions in this region, but the source of the hot electrons (up to 800 eV) is not known. There are also significant fluxes of energetic ions (>40 keV) in the outer region with energy densities approaching that of the magnetic field.

The flow of the plasma is essentially corotational, with little evidence for convective or radial flows. Beyond ~ 8 R_S, the plasma velocity falls 10% to 20% below full corotation, consistent with a modest, but nonnegligible, estimated mass-loading rate of ~ 7 kg s^{-1} from Titan's atmosphere. Thus, corotation in the outer magnetosphere may be only marginally maintained by the torque supplied by Saturn's ionosphere.

C. Energetic Particles

The nature of the trapped radiation is determined by the sources, sinks, and motions of the energetic particles (see the chapters by Van Allen and by Schardt, Behannon, Lepping, Carbary, Eviatar, and Siscoe). The principal source for electrons and protons with energies of 30 keV to 2 MeV is in the outer magnetosphere, possibly thermalized solar wind or solar energetic particles. The fluxes of these particles are highly variable in the hot outer magnetosphere ($\geq$ 15 R_S). Inside this radius, the particles diffuse inward across the region of the extended plasma sheet, undergoing few losses until reaching the satellites in the inner magnetosphere ($\leq$ 8 R_S).

In the inner region (see the chapter by Van Allen) the particles undergo significant losses as they diffuse inward and are swept up by the succession of satellites, resulting in phase space densities at 4 R_S that are $\leq 10^{-3}$ of those beyond 8 R_S. Electrons with ~ 1 MeV are less attenuated, however, because their drift velocities relative to Saturn nearly match the orbital velocities of the satellites. As a result, they are less likely to collide with a satellite in the time it takes to diffuse across its orbit. Thus, the system of satellites behaves as a bandpass filter. The particles that do diffuse past the inner satellites without loss are totally absorbed upon reaching the outer edge of the A Ring.

The average rate of loss of particles to satellite sweeping can be used to estimate the radial diffusion rate, as can the rate at which particles fill in the void created by individual satellites. Estimates of diffusion coefficients range from 10^{-8} to $10^{-10} R_S^2 \, s^{-1}$ in the inner magnetosphere. Although the nature of the diffusion process is not known, the derived radial dependence of the diffusion coefficient ($\sim L^3$) in the 4 to 8 R_S region is more consistent with diffusion driven by ionospheric winds than with centrifugally driven diffusion as occurs in the Io plasma torus.

Particle absorption effects can also be used for other studies, such as determination of the tilt and offset of the magnetic field (see the chapter by Connerney et al.) and the search for previously unknown satellites and rings. Absorption signatures provided the first evidence for several such objects (see the chapter by Van Allen).

Although inwardly diffusing particles are totally absorbed by the A Ring, the rings are also sources of trapped particles. Significant fluxes of trapped high-energy ($\geq$ 16 MeV) protons result from cosmic ray albedo neutron decay (Crand). The energetic albedo neutrons are produced in the interaction of cosmic ray nuclei ($E \geq 20$ GeV) with the icy ring material; they decay during flight, becoming trapped protons with typical energies of $\sim$ 40 to $\sim$ 100 MeV.

There is also evidence for other sources of particles in the magnetosphere. In the inner region, there are indications of sources of low-energy ions ($\sim$ 30 keV) and electrons ($\sim$ 500 keV), although the nature of such sources is unknown. There are also indications that 200 keV electrons are accelerated in the magnetotail as at Earth and Jupiter, although the observations are again too limited to determine the acceleration process. The magnetotail may also be involved in the acceleration of MeV ions (H, H_2, H_3, He, C, O) observed in the outer magnetosphere. The molecular ions are likely of ionospheric origin, while the He, C, and O ions are of solar wind origin.

D. Saturn's Kilometric Radiation (SKR)

Kilometric radiation is the principal radio emission from Saturn, occurring over a frequency range from 3 kHz to 1.2 MHz, with peak intensity at 175 kHz (see the chapter by Kaiser et al.). The strongest source is in the northern auroral region, with maximum intensity occurring when a particular range of longitudes (100° to 130° SLS) is near local noon. There is evidently an anomaly in the magnetic field at this longitude which allows access of solar wind plasma electrons deep into the polar cusp where radiation is generated near the local electron gyrofrequency. There is a similar, but weaker, source region in the southern auroral zone. Radiation observed in the northern hemisphere is right-hand polarized, probably circular, while that in the southern hemisphere is left-handed.

The localization of the source region in both longitude and local time results in the occurrence of SKR episodes with an average periodicity of 10 hr 39 min 24 ± 7 s, which is presumed to be the period of rotation of Saturn's magnetic field and deep interior. This SKR period is the basis for a new Saturn longitude system (SLS).

The energy source for SKR is the impinging solar wind, and changes in solar wind pressure or speed produce marked changes in SKR power. For example, a pressure increase by a factor of 150 results in a 10 times increase in SKR. The typical SKR power is 200 MW, corresponding to $\sim 5 \times 10^{-5}$ of the average solar wind power incident on the magnetosphere. Peak SKR power ranges up to 50 GW.

There was a period of 2 to 3 days immediately following the Voyager 2 encounter, however, when the SKR was undetectable ($\leq 10^{-4}$ of nominal), possibly due to the absence of solar wind flux resulting from the immersion of the Saturnian magnetosphere in the extended Jovian magnetotail. The magnetosphere was observed to be greatly inflated during this time and Jovian-like continuum radiation was detected. These observations of solar wind control of SKR are consistent with a model involving transfer of solar wind particles deep into the magnetosphere via the cusp region.

E. Titan Magnetosphere Interaction

The immersion of Titan in Saturn's corotating magnetosphere provided the opportunity for a unique study by Voyager 1 of the interaction of a plasma wind and a planetary atmosphere (see the chapter by Neubauer, Gurnett, Scudder, and Hartle). The incident magnetospheric plasma velocity of ~ 120 km s^{-1} was transalfvénic ($M_A \sim 1.9$) and subsonic ($M_s \sim 0.57$), a condition under which no bow shock occurs and which had not been previously observed.

In the resulting smooth flow around Titan, the ambient Saturnian magnetic field is loaded with H^+, N^+, and N_2^+ or H_2CN^+ ions from Titan's exosphere. The mass loading from the heavy ions slows the regions of the magnetic field lines closest to Titan down to < 10 km s^{-1}, causing them to drape behind Titan in a comet-like tail. The induced magnetotail has a neutral sheet separating northern and southern lobes which are surrounded by a magnetopause plasma of heavy ions.

Mass loading is most effective on the sunlit side of Titan, resulting in an asymmetric plasma flow and magnetotail. The plasma interaction with the colder nightside atmosphere may be somewhat similar to that of the solar wind with Venus, while that with the hotter day side may resemble more the interaction of the solar wind with a comet.

III. THE RINGS

Since they were first observed by Galileo in 1610, the nature of Saturn's rings has been a continuing challenge to observation and theory (see the chapter by Van Helden). The structure of the rings is determined by their origin and by dynamical processes which depend upon the sizes and collisional properties of the ring particles, on the gravitational effects of the satellites and of Saturn's oblateness, and on electromagnetic processes (see the chapters by Esposito, Cuzzi, Holberg, Marouf, and Porco, and by Mendis, Hill, Ip, Goertz, and Grün). Determining the origin of the rings depends on understanding these dynamical processes and physical properties.

A. General Properties

The classical ring system consists of three broad rings (A, B, and C) occupying the region between 1.23 R_S and 2.67 R_S in Saturn's equatorial plane (see Table I). With the exception of the E Ring, the others are too diffuse or too narrow to be observed from Earth. The D Ring fills much of the region between the C Ring and the top of Saturn's atmosphere, while the E, F, and G Rings lie beyond the main rings. Both the F and G Rings are relatively narrow, while the E Ring occupies an extended region about the orbit of Enceladus.

The optical albedo of the A Ring and B Ring is ~ 0.6 and the microwave albedo is nearly unity. The C Ring and the Cassini Division have a somewhat lower optical albedo of ~ 0.2. The color of individual particles in these regions may be similar, although the thinner C Ring and Cassini Division appear to be less reddish. The particles in the main rings have icy surfaces, consistent with an assumed bulk composition of water ice. They range in size from millimeters up to ~ 5 m in radius, with particle numbers decreasing approximately as a^{-3} with increasing radius a. It is estimated that the mass of the rings is $\sim 6 \times 10^{-8}$ M_S, about that of an icy satellite such as Mimas. However, this mass is somewhat uncertain, since the bulk of it is in the B Ring for which the relevant particle-size distributions have not yet been directly determined.

The observed segregation of the main rings into large, distinct regions is a result not only of the primordial distribution of the matter, but also of the dynamical processes which have maintained the segregation. As described below, satellite resonances form an effective barrier to the outward diffusive flow of particles. There is, however, no known physical mechanism which prevents the inward flow of particles into adjacent ring regions.

B. Specific Properties

A Ring. This outermost of the classical rings is relatively unstructured with a typical normal optical depth of ~ 0.5. Although most of the opacity is due to particles with radii $a > 1$ cm, of which there are typically ~ 20 m^{-2}, about one quarter is due to a larger number of millimeter-sized particles.

TABLE I
Dimensions of the Rings of Saturn

Feature Distance from Saturn Center	(R_S)[a]
D Ring inner edge	1.11
C Ring inner edge	1.23
Maxwell Gap	1.45
B Ring inner edge	1.53
B Ring outer edge	1.95
Huygens Gap	1.95
Cassini Division	1.99
A Ring inner edge	2.02
Encke Gap	2.21
Keeler Gap	2.26
A Ring outer edge	2.27
F Ring center	2.33
G Ring center	2.8
E Ring inner edge	3
E Ring outer edge	8

[a] 1 R_S = 60,330 km. Distances are given for the center of gaps and divisions.

The outer edge of the A Ring occurs at a radial location where the orbital period of the ring particles is 6/7 that of Janus. This orbital resonance provides a mechanism for exchanging angular momentum between the ring particles and Janus, effectively forming a barrier to their outward motion. It is not understood, however, why this exchange has not forced Janus outward, since its angular momentum should noticeably increase in $< 10^7$ yr.

There are many other locations in the A Ring where there are weaker orbital resonances, most of them with S15 and S16, the small shepherd satellites of the F Ring. Perturbations in the density of ring particles are generated at the locations of these weaker resonances, launching outward-moving spiral density waves. The wavelength of the waves depends on the surface mass density, which is typically $\sim$ 50 g cm^{-2}.

There are also spiral bending waves in the A Ring generated by Mimas which has a slightly inclined orbit and therefore perturbs the motion of the ring particles perpendicular to the ring plane. The vertical amplitude of these waves ($\sim$ 0.7 km) could be a major factor in the apparent thickness of the rings when viewed edge on. The rate of damping of these waves indicates that the dispersion velocity of the particles is $\sim$ 4 mm s^{-1}, leading to a dynamical ring thickness of $\sim$ 35 m which is consistent with the upper limit of 200 m determined at sharp boundaries in the ring.

There are two narrow gaps in the outer portion of the A Ring which are not due to resonances with external satellites, but are likely due to undiscovered moonlets within the gaps. The Encke Gap has wavy edges and contains a kinky ringlet, further indications of several imbedded moonlets.

B Ring. This ring, which is separated from the A Ring by the Cassini Division, is the largest and brightest of the three classical rings, with optical depths ranging from 0.7 to > 2. Almost half of the opacity is due to subcentimeter-sized particles, indicating their greater relative abundance than in the A Ring. The surface mass density of the B Ring is not well known, but is estimated to average $\sim$ 100 g cm^{-2}, twice that of the A Ring.

The outer boundary of the B Ring, which occurs at the Mimas 2:1 resonance, has a double-lobed pattern that precesses with Mimas' angular velocity as expected theoretically. Thus, the outward diffusion of particles in the B Ring is inhibited by the resonant transfer of angular momentum to Mimas, which subsequently transfers it to Tethys through another 2:1 resonance (see the chapter by Greenberg).

Although there are few other significant resonances within the B Ring, it displays much more structure than the A Ring. The structure is essentially chaotic on all scales $<$ 15 km. There is currently no physical model for the structure, although diffusional instability may have some role. Since there are no gaps in the B Ring, the structure is not that of numerous discrete ringlets. Plasma instabilities and meteoroidal erosion may contribute to the largest scale structure (see the chapter by Mendis et al.).

Spokes are another B Ring phenomenon for which a complete physical model is lacking, although their tendency to occur with the rotational period of the magnetic field and at the same longitude as Saturn kilometric radiation suggests that electromagnetic processes are involved. A number of proposed models are discussed in the chapter by Mendis et al. The spokes are cloud-like distributions of micron-sized particles that appear sporadically in the region between $\sim 1.75\ R_S$ and $\sim 1.9\ R_S$ and are most often apparent in the morning sector of the rings. Some of the spokes appear to form radially over thousands of kilometers in $<$ 5 min, with subsequent Keplerian motion producing wedge-shaped patterns.

C Ring and Cassini Division. There are a number of similarities in these two regions. Both have typical optical depths of $\sim$ 0.1, with several clear gaps and eccentric opaque ringlets, and both have relatively fewer particles with radii $a < 1$ cm. The Cassini Division contains five broad, diffuse rings separated by narrow gaps. The wider Huygens Gap occurs at the inner edge of the division and contains an opaque eccentric ringlet that precesses at a rate governed by Saturn's oblateness. The maintenance of such a gap and narrow ringlet would seem to require imbedded moonlets, although none have been found. Similar opaque ringlets are located in the Maxwell Gap in the C Ring and in a gap at the Titan apsidal resonance at 1.29 R_S. There are several other dense ringlets in the C Ring at the boundaries of gaps occurring at resonances with Mimas. No mechanism is known at present for producing such ringlets.

Other Rings. The E Ring is broad and diffuse, composed predominantly of micron-sized particles. It occupies the region between 3 R_S and 8 R_S and is several thousand kilometers thick. The optical thickness of the ring is only $\sim 10^{-7}$, and it can be observed from Earth only when viewed edge on. The maximum density occurs near Enceladus' orbit, suggesting that this satellite is the source of the E Ring. Such small particles have lifetimes of $< 10^4$ yr before being destroyed by charged particle sputtering and must be resupplied, possibly by meteoroidal impacts (see the chapter by Mendis et al.).

The F Ring also contains numerous micron-sized particles which are distributed in multiple narrow strands over a region several hundred kilometers wide. The core of the F Ring does include centimeter-sized particles, and there is evidence for larger objects or clumps. The ring particles are shepherded between S15 and S16, receiving angular momentum from the inner shepherd and transferring it to the outer shepherd. However, the processes responsible for the multiple strands and for the occasional kinkiness of the F Ring are not yet understood.

Much less is known about the D Ring and G Ring. Both have very small optical depths and cannot be seen from Earth. The broad D Ring has relatively few micron-sized particles, while the optical depth of the narrow G Ring is dominated by such small particles. Neither the structure in the D Ring nor the narrowness of the G Ring are understood.

IV. SATELLITES

Saturn has 17 satellites with orbits that are currently well known (see Table II), as well as several others that have been less well determined (see the chapters by Morrison, Johnson, Shoemaker, Soderblom, Thomas, Veverka, and Smith, and by Cruikshank, Veverka, and Lebofsky). The group of seventeen appears to contain four distinct classes of objects. Only Titan is a major satellite, comparable in size to Ganymede, but with the distinctive attribute of a dense atmosphere. Six others, Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus, represent a new class of intermediate-sized icy satellites, with radii ranging from 197 to 765 km. Except for Phoebe, the remainder comprise another new class of objects that probably are icy fragments of larger bodies. Phoebe is the only one thought to be a captured object. As described in the chapter by Greenberg, orbital resonances have been important in determining the structure of the satellite system.

TABLE II
Satellites of Saturn

Satellite	*a* (R_S)	*R* (km)
S17 Atlas	2.276	20 × ? × 10
S16 1980S27	2.310	70 × 50 × 37
S15 1980S26	2.349	55 × 45 × 33
S10 Janus	2.51	110 × 95 × 80
S11 Epimetheus	2.51	70 × 58 × 50
S1 Mimas	3.08	197 ± 3
S2 Enceladus	3.95	251 ± 5
S3 Tethys	4.88	530 ± 10
S13 Telesto	4.88	15 × 10 × 8
S14 Calypso	4.88	12 × 11 × 11
S4 Dione	6.26	560 ± 5
S12 1980S6	6.26	17 × 16 × 15
S5 Rhea	8.73	765 ± 5
S6 Titan	20.3	2575 ± 2
S7 Hyperion	24.6	205 × 130 × 110
S8 Iapetus	59	730 ± 10
S9 Phoebe	215	110 ± 10

A. Intermediate-Sized Icy Satellites

As a class, Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus share a number of common characteristics. All have average densities between ~ 1.2 and ~ 1.4 g cm^{-3}, indicating an ice/rock mixture which is likely 60% to 70% H_2O ice, consistent with the spectral identification of H_2O ice on their surfaces and with a high albedo of ~ 0.4 to 1 for all but the dark side of Iapetus. Generally, there appears to be more frost on their surfaces than on Ganymede and Callisto and variations in albedo are thought to result partly from differences in the admixture of neutrally colored dust. Unlike the Galilean satellite system, there is no indication of major changes in bulk composition with radial distance. There is, however, an increase in size with distance from Saturn.

The five inner intermediate-sized satellites show varying evidence for endogenic activity such as surface flooding, troughs, ridges, and grooves, most having occurred in the first few hundred million years of the satellites' geologic history. It has been suggested that liquid magma resulted from a low-density water-ammonia eutectic with a low melting point (173 K), since it would be more readily melted by the limited amount of radioactive heating in such small, icy bodies and would naturally rise through fractures in the denser ice.

Endogenic activity has been even more vigorous on Enceladus, with the most recent activity occurring in the last 10^9 yr, possibly even during the last 10^8 yr. The high albedo of this satellite ($p_V \sim 1.0$) and its association with the E Ring also suggest internal activity which produces fine particles that populate the ring and keep the surface bright. Five distinct terrains have been identified, with the youngest plains regions containing grooves which may be extensional fractures similar to those on Ganymede. The degree of relaxation of impact craters also differs markedly in different regions, indicating large differences in viscosity due to differences in composition and heat flow. The only known source of heat sufficient to cause the level of activity on Enceladus is tidal dissipation, although the current rate of dissipation is inadequate to cause melting (see the chapter by Greenberg) and may be only marginally adequate to maintain a liquid interior that might have been melted during an earlier epoch.

The dark side of Iapetus may also result from endogenic processes which bring a dark magma (albedo < 0.05) to the surface of the icy satellite. However, the symmetrical placement of the dark material with respect to Iapetus' leading hemisphere seems to require either that the distribution of endogenic material is controlled by impacts or that the dark material is of external origin. Currently the origin of the dark material remains undetermined.

The surfaces of the intermediate-sized satellites also indicate the importance of exogenic processes in the Saturnian system. All six satellite surfaces show extensive impact cratering, with at least two crater populations produced by different groups of impacting objects: population 1, containing a relatively large abundance of craters with diameters $D > 20$ km, and population 2, containing an abundance of craters $D < 20$ km and few larger.

Population 1 craters are thought to have been created during the tail-off of a postaccretional bombardment, possibly by bodies of external origin. Subsequently, population 2 craters may have been created by secondary objects in orbit about Saturn, possibly the debris from earlier collisions. There is an abundance of population 1 craters on Rhea, Dione, Tethys, and the bright side of Iapetus. The younger plains regions on Dione and Tethys contain population 2 craters, as does most of the surface of Mimas. Enceladus shows only population 2 craters, indicating that its entire surface has been modified since the postaccretional bombardment.

The abundance of population 1 craters on Iapetus has significant implications for the history of the inner satellites if the impacting bodies were of external origin and if their size distribution extended to larger diameters. In such a case, gravitational focusing would have resulted in several impacts that were large enough to disrupt the inner satellites which would then have subsequently reaccreted. Although the small satellites and the rings may be the remains of such disruptive collisions, the implied flux of impacting objects is much larger than is currently estimated for comets, the only known external source. If, instead, the impacting objects were lower-velocity objects associated with Saturn, then disruptive collisions might not have been prevalent. In this case, population 1 and 2 craters may result from different temporal behavior of large and small objects in orbit about Saturn.

B. Small Satellites

With the exception of Phoebe, the small satellites are irregularly shaped objects which are likely fragments of larger bodies. Hyperion is the largest of the small satellites with a major dimension only slightly smaller than the diameter of Mimas. Although Hyperion is not heavily cratered, the presence of population 1 craters indicates a relatively old surface consistent with fracture of the parent body near the end of postaccretional bombardment. Although Hyperion's density is unknown, there is dirty water ice on its surface, suggesting an icy bulk composition like that of the larger satellites. The uniformly reddish color of Hyperion's surface is similar to, but brighter than, the dark side of Iapetus, possibly resulting from similar carbon-bearing materials. Hyperion's lack of hemispherical asymmetry such as is observed on Iapetus is now understandable with the recognition that the pendulum-like motion associated with its elongated shape results in chaotic rotational motion. Thus, it is possible that some of the dark material swept up by Iapetus has also coated Hyperion, if the exogenic origin of Iapetus' albedo asymmetry is indeed correct.

The other irregularly shaped satellites are smaller and are closer to Saturn. All have relatively bright surfaces with albedos greater than 0.4 and colors like those of the intermediate-sized icy satellites, suggesting a similar surface composition of dirty water ice. The presence of impact craters indicates the surfaces are at least several billion years old. Both Epimetheus and Janus show heavy cratering which is characteristic of the end of the postaccretional bombardment.

These smaller satellites are in dynamically interesting orbits (see the chapter by Greenberg). For example Calypso and Talesto are located in the two stable regions associated with the Lagrangian points in Tethys' orbit, S12 resides in a similar region in Dione's orbit, Janus and Epimetheus are coorbitals which periodically exchange energy so as to avoid collision, and S15 and S16 are shepherd satellites, dynamically constraining the narrow F Ring between them. As described above, several of the smaller satellites have important dynamical effects on the A Ring.

Phoebe's retrograde inclined orbit is also of interest because it indicates that Phoebe is likely a captured object and may be fundamentally different from the other Saturnian satellites. Although small, Phoebe is approximately spherical, and its surface is dark and somewhat patchy with a reddish color suggestive of that of a C-type asteroid and unlike that of the dark side of Iapetus. However, the lack of knowledge of Phoebe's bulk composition and uncertainties in its surface properties preclude a determination of the nature and origin of this intriguing object.

C. Titan

The Voyager encounters with Titan have effectively added a new world to the solar system (see the chapters by Hunten, Tomasko, Flasar, Samuelson, Strobel, and Stevenson, and by Sagan, Khare, and Lewis). This satellite possesses a predominantly nitrogen atmosphere denser than Earth's, in which a fascinating variety of chemical and physical phenomena are occurring. The surface pressure on Titan is 1.5 bar, the temperature 94 ± 2 K. While methane was first detected in Titan's atmosphere by G. P. Kuiper in 1944, the exact abundance of this gas is still poorly known. There is apparently not enough methane in Titan's lower atmosphere to permit the formation of a global methane ocean, but lakes and seas of this hydrocarbon cannot be ruled out. A global ocean of ethane is more likely, however. Argon 36 and 38 may also be present, at a level of a few percent, since the uncertainty in the mean molecular weight derived from the radio occultation and infrared experiments would permit a significant amount of some very volatile, cosmically abundant species that is heavier than nitrogen and spectroscopically undetectable. Argon satisfies all of these constraints and would be expected if the main source of Titan's atmosphere is the decomposition of clathrate hydrates.

Currently, twelve other species besides molecular nitrogen and methane have been identified in Titan's spectrum. With the possible exception of carbon monoxide (which may be primordial), all of these compounds are produced by chemical reactions in Titan's atmosphere. Solar ultraviolet and the bombardment of electrons from Saturn's magnetosphere furnish the necessary energy. These trace constituents include hydrogen cyanide, an important compound in simulations of prebiological organic chemistry on the early Earth.

The atmospheric chemistry produces increasingly complex molecules that comprise the ubiquitous aerosol totally hiding Titan's surface from view. The uppermost particles in this aerosol layer have mean sizes of a few tenths of a micron. Their composition remains uncertain; both theoretical calculations and laboratory simulations point toward a mixture of organic polymers. The surface of Titan must therefore be covered with a layer of aerosols deposited from the atmosphere as well as solid and liquid hydrocarbons. If ethane is the dominant end product, a global ethane ocean with a depth of 1 km could be present. The concomitant destruction of methane implies a source of this gas on or in the satellite. Seas of liquid methane or an ocean of ethane with dissolved methane may buffer the system. A steady-state concentration of H_2, another product of methane photochemistry, is present in Titan's atmosphere, while photochemically-produced hydrogen continually escapes the satellite's weak gravitational field, contributing to a torus around Saturn.

The absence of features in the aerosol layers has prevented any mapping of atmospheric winds. The temperature gradient in the atmosphere implies a cyclostrophic circulation and the north-south asymmetry in the aerosol brightness is another clue that motions are in fact occurring in the atmosphere. At the surface, a modest greenhouse effect maintains a nearly-uniform temperature ~ 10° above the solar equilibrium value.

The mean density of Titan indicates the presence of a rocky core surrounded by ice. This ice could include clathrate hydrates and/or ammonium monohydrate. The size of the rocky core indicates an enrichment of silicates compared to predictions from cosmic abundances. Models for the formation of Titan include the possibility of a hot, postaccretional phase in which a massive atmosphere containing ammonia could exist. If this phase lasted sufficiently long, it could provide another pathway toward the formation of the present N_2 atmosphere by photodissociation of the NH_3.

V. ORIGIN AND EVOLUTION

Many authors have suggested that both Jupiter and Saturn formed as a result of the condensation of giant, gaseous protoplanets from the solar nebula. In recent years, this hypothesis has been challenged and support has grown for a heterogeneous accretion model in which all four of the giant planets formed by the same process: accretion of a core dominated by rock and/or ice followed by hydrodynamic collapse of an envelope of nebular gases (see the chapter by Pollack and Consolmagno). The model predicts that all four planets should have cores of approximately the same size (10–20 $M_{\odot}$), indicating the mass at which instability is induced in the nebula. The smaller masses of Uranus and Neptune are then the result of a smaller "captured" nebular envelope, perhaps because the collapse phase took place at a time when much of the nebular gas had been dissipated. Furthermore, the enrichment of heavy elements in the atmospheres of all four planets—manifested most clearly by the value of CH_4/H_2—is also consistent with this model.

There are, however, many differences between Jupiter and Saturn. Chief among these are the larger relative core size of Saturn, the probable dominance of helium precipitation as a source of internal energy, and the ubiquity of ice in the system of icy satellites and the magnificent icy rings. All the satellites except Phoebe presumably formed with the planet. Phoebe's retrograde orbit and great distance from Saturn both suggest that it is a captured object. Capture would be easiest at a very early stage in the system's evolution, when a greatly extended "atmosphere" was present to slow down an object passing through it.

The nature of the internal source of heat as well as the relative importance of ice in the Saturn system seem closely related to the smaller mass of the planet. Whatever process led to its formation, Saturn evidently originated from a region of the solar nebula with less total mass available to the forming planet than was available at Jupiter. Model calculations suggest that at the end of the hydrodynamical collapse (either of the condensing protoplanet or the nebular envelope onto the accreted core), the radius of Saturn was several times the present value and a nebular disk existed in the equatorial plane. The regular satellites and perhaps the rings developed from this disk, some 10^8 yr after the planet began to form. From this point, further contraction first led to an increase in luminosity, then to a decrease as the planet cooled down. Homogeneous contraction and thermal cooling produced excess internal energy that adequately explains the infrared flux observed from Jupiter, but the value predicted for Saturn is only marginally compatible with the observations. Hence the preference for the helium precipitation theory, which is further substantiated by the observed depletion of helium in the planet's atmosphere.

Formation of the rings and satellites in the nebular disk left in the equatorial plane will be determined by local pressure and temperature. Unlike Jupiter's satellites, Saturn's moons show no evidence of a radial gradient in mean density, thereby providing a useful constraint on models of this disk. Given the predicted luminosity of Saturn, it is possible to construct models that allow the progressive condensation of ices as temperatures fall in the nebular disk in response to the cooling of the planet. An example of such a model predicts water ice at Mimas and Enceladus, ammonium monohydrate at Tethys and Dione, with a mixed clathrate of methane, argon, nitrogen (and possibly CO) becoming likely at the distances of Titan and Iapetus. This condensation sequence would not affect the observed mean densities (rocky material would be available throughout), but does provide the wherewithal for Titan's atmosphere. The latter is certainly not a captured remnant of the primordial nebula since it contains less than one percent neon. The smaller sizes of Mimas and Enceladus may result from later accretion owing to the delay in cooling of the inner region of the nebula.

The observed modification of the surface of Enceladus remains an enigma. The existing orbital resonance between Enceladus and Dione will not produce enough tidal heating to cause melting, even if an ammonia eutectic composition is invoked. Either the forced eccentricity of the orbit was greater in the recent past ($<10^9$ yr), or some other energy source must be identified.

The formation of the rings is viewed as a special case of the same condensation and accretion processes that produced the regular satellites. They would have begun to form as soon as the temperature in the disk at the position of the rings fell below about 240 K, some 5×10^6 yr after the termination of the collapse phase. Since the ring material was inside the Roche limit, the gradient of Saturn's gravitational field was larger than the mutual gravity between any two ring particles, preventing the formation of large objects. Additional studies of the rings are required to set an upper limit on the sizes of objects that did form within this limit. Possible imbedded satellites remain an attractive explanation for some of the observed gaps in the rings, but no such satellites have yet been observed.

VI. CONCLUSION

The chapters in this book describe in detail the current state of knowledge of the Saturn system. Not only has there been a great increase in our understanding of this unique system, but enough is now known to be able to pose basic questions which previously would have been based on little more than speculation. Further analysis of available data and new theoretical considerations will address some of these questions, as will new groundbased and Space Telescope observations. However, the answers to many of the new questions will have to await the eventual return to the Saturn system by orbiting spacecraft and atmosphere probes.