Chapter 15
Ring Particle Composition and Size Distribution

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Abstract We review recent progress concerning the composition and size distribution of the particles in Saturn’s main ring system, and describe how these properties vary from place to place. We discuss how the particle size distribution is measured, and how it varies radially. We note the discovery of unusually large “particles” in restricted radial bands. We discuss the properties of the grainy regoliths of the ring particles. We review advances in understanding of ring particle composition from spectrophotometry at UV, visual and near-IR wavelengths, multicolor photometry at visual wavelengths, and thermal emission. We discuss the observed ring atmosphere and its interpretation and, briefly, models of the evolution of ring composition. We connect the ring composition with what has been learned recently about the composition of other icy objects in the Saturn system and beyond. Because the rings are so thoroughly and rapidly structurally evolved, the composition of the rings may be our best clue as to their origin; however, the evolution of ring particle composition over time must first be understood.

15.1 Introduction

Cassini will revolutionize our understanding of the composition and size distribution of the particles making up Saturn’s main rings. We say “will” with confidence, because only a fraction of the relevant data obtained by Cassini during its 4-year prime mission has actually been thoroughly analyzed as of this writing. At this time, only very broad regional averages of various observable properties have been looked at; characterizing the most opaque regions, or increasing radial resolution, will require more sophisticated data analysis; also, instrumental calibration remains in flux to some degree. In this chapter, we provide a sense of the direction indicated by the current sample of newly analyzed data. We will emphasize Cassini results (comparing them with Earth-based results that have not been reviewed previously). A very thorough pre-spacecraft historical review is provided by Pollack (1975). A series of extensive reviews covering ring particle composition and size from the Voyager era includes Cuzzi et al. (1984) and Esposito et al. (1984). Some post-Voyager reviews that include more recent work include Cuzzi (1995), Dones (1998) and Cuzzi et al. (2002). A short meta-review of the pre-Cassini status may be found in this volume (Chapter 2).

The composition and size distribution of the particles in Saturn’s main rings are tied together from the observational standpoint, and both are key factors in any serious modeling of the origin and evolution of the main rings (Chapter 17). The fact that the ring composition evolves with time is a fairly recent insight; the particle composition can change as particles are irradiated by photons, bombarded by magnetospheric and/or ionospheric particles or primitive interplanetary meteoroids, or perhaps as they interact chemically or mineralogically with their locally produced oxygen atmosphere. For instance, it has long been known that water ice constitutes the bulk of the ring material (Chapter 2); however the rings are noticeably red at visual wavelengths, manifesting the presence of another substance. Moreover, interplanetary debris is primarily non-icy material – silicates and carbon-rich organics – so the rings become increasingly “polluted” over their lifetime. The degree to which this happens depends critically on the local particle size and surface mass density. Only by understanding the evolutionary processes that transpire in the rings can we look back from their current state to infer their primordial state, and thus get a clue...
as to their provenance (Chapter 17). The way in which the ring composition is observed to vary with local ring properties will provide important evidence that will allow us to understand and unravel this evolution.

Our chapter is divided into six sections. In Section 15.2, we review the size distribution of the particles in the main rings, sketching several methods by which particle size distributions are inferred. Ring particles range in size from a centimeter to meters or perhaps tens of meters, and the particle size distribution (in particular the abundance of 1–10 cm particles) changes dramatically across the rings. We comment on the distinction between “particles” and transient, dynamical entities composed of particles. In Section 15.3 we briefly describe Cassini’s discovery of an entirely new class of “particles” – objects hundreds of meters across which make their presence known only by their disturbance of surrounding material, and summarize their implications for the ring mass. In Section 15.4, we discuss what we have learned about the composition of the particles in the main rings, primarily from remote sensing spectroscopy and photometry. The rings are composed almost entirely of water ice – in its crystalline phase and of unusual purity – but the puzzle of the reddening material – the so-called “UV absorber” has perhaps even deepened. A combination of laboratory studies of icy mixtures, theoretical models, and analogies with other icy objects are employed to interpret these observations. In Section 15.5, we discuss two possible evolutionary influences on ring composition. The ring atmosphere was newly characterized by Cassini to be composed not of the expected water products (OH and H), but of O atoms and O₂ molecules. Such chemically reactive molecules might play a role in the compositional evolution of the rings. In this section we also briefly describe some of the issues related to compositional evolution by meteoroid bombardment, deferring to the Chapter 17 for the details. Finally, in Section 15.6, we broaden the discussion connecting ring composition to ring provenance, comparing the properties of the main ring material to those of Saturn’s icy moons, icy moons of other systems, and icy and non-icy outer solar system objects.

15.2 Ring Particle Size Distribution

Ring particle size information is captured in observations of the interaction of electromagnetic radiation with the ring material. In general, the particle sizes, shape, composition and spatial distribution (clustering, packing, and spread normal to the mean ring plane) control the manner in which the electromagnetic radiation is extinguished and scattered in all spatial directions. The size information is usually captured, along with the other physical properties, in several types of Earth-based and spacecraft observations, which we review here. Readers interested only in results rather than methods can skip to Sections 15.2.8 and 15.2.9.

Radio and stellar ring occultations provide two especially sensitive ways to determine ring particle sizes, because of their near-forward-scattering observation geometry. The first is direct measurement of the extinction of the incident electromagnetic radiation passing through the rings and hence oblique optical depth, a parameter especially sensitive to the particle sizes relative to the radiation wavelength. The second is indirect measurement of the near-forward scattering pattern; that is, of the collective diffraction-lobe. The lobe shape and width are primarily controlled by the particle size distribution and are relatively insensitive to particle composition and shape.

15.2.1 Models and Theory

Modeling the interaction of electromagnetic radiation with the rings has been traditionally based on the so-called “classical” model. The model is rooted in radiative-transfer-like approaches to the electromagnetic interaction problem, where the particles are assumed to be uniformly distributed in a loosely-packed, extended layer many-particles-thick. No particle clustering is assumed, although individual large particles can be thought of as ephemeral aggregates of densely packed smaller particles (Marouf et al. 1982, 1983; Tyler et al. 1983).

Dynamical simulations and observations provide compelling evidence for the prevalence of “gravitational wakes”, or extended transient structures which form by virtue of the self-gravity of the ring particles, nearly across the full extent of Rings A and B (Chapters 13 and 14). Particles within the wakes form chains of spatially correlated canted and elongated clusters, invalidating basic assumptions of the classical model. Extension of the electromagnetic interaction problem to include wake models is an ongoing endeavor. We base the discussion below on the classical model for the lack of a better electromagnetic interaction model at this time and to enable comparison with results of previous published work. Preliminary results regarding the impact of wakes on extinction and forward scattering observations are discussed briefly in Section 15.2.10.

For the classical ring model, the normal optical depth \( \tau \) and its oblique value \( \tau_q \) are related by \( \tau_q = \tau / \mu_0, \mu_0 = \sin(|B|) \), and \( B \) is the ring opening angle (the angle between the planet-observer line and the ring plane). The optical depth \( \tau \) is given by

\[
\tau(\lambda) = \int_0^\infty \pi a^2 Q_e(a, \lambda) n(a) \, da \quad (15.1)
\]

where \( Q_e(a, \lambda) \) is the extinction efficiency of a spherical particle of radius \( a \), \( \lambda \) is the radiation wavelength, and \( n(a) \) is
the size distribution (particles m\(^{-2}\) m\(^{-1}\)). Dependence on the particle composition is implicit in \(Q_c\). In principle, measurements of \(\tau(\lambda)\) at several \(\lambda\) may be used to invert the integral equation to recover \(n(a)\). Alternatively, parameters of an assumed model of \(n(a)\) may be constrained by matching predictions based on the integral above to the observed \(\tau(\lambda)\). A commonly adopted model is the power-law model, where

\[
n(a) = n_0 \left(\frac{a}{a_0}\right)^{-q}, \quad a_{\text{min}} \leq a \leq a_{\text{max}},
\]

and is zero otherwise. It is characterized by the minimum radius \(a_{\text{min}}\), the maximum radius \(a_{\text{max}}\), the value \(n_0\) at an arbitrary reference radius \(a_0\), and the power-law index \(q\).

When \(\tau\) is small, multiple scattering effects can be neglected and the single scattered near-forward signal intensity \(I_1(\theta, \lambda)\) relative to the “free-space” incident power per unit area \(I_i\) can be approximated by

\[
I_1(\theta, \lambda)/I_i = \frac{e^{-\tau/\mu_0}}{4\pi \mu_0} \int_{a_c}^{\infty} \pi a^2 \left[\frac{2J_1(ka \sin \theta)}{\sin \theta}\right]^2 n(a) \, da
\]

where \(k = 2\pi/\lambda\), \(J_1\) is the Bessel function of first kind and order 1, \(a_c\) is a lower bound on the radius \(a\) of particles effectively contributing to the scattered signal, and \(\theta\) is the scattering angle. The particles are assumed large compared to the wavelength \((ka > ka_c >> 1)\). Here too, the size distribution \(n(a)\) may be recovered from the measured \(I_1(\theta, \lambda)\) using integral inversion. Alternatively, parameters of an assumed power-law model of \(n(a)\) may be constrained by matching computed values of the right-hand side to the observed collective diffraction pattern \(I_1(\theta, \lambda)/I_i\). The approach applies equally to \(\lambda\)’s in the ultraviolet, visible, infrared, and radio spectral regions.

For realistic optical depths of order unity, the effects of multiple scattering on the observed near-forward scattered signal \(I_s(\theta, \lambda)/I_i\) must first be deconvolved to recover the single scattered component \(I_1(\theta, \lambda)/I_i\). In the case of scattering by particles of optical size \(ka >> 1\), and assuming a classical ring model, it is possible to express \(I_s(\theta, \lambda)/I_i\) as the sum of terms each representing a distinct order of scattering (Marouf et al. 1982, 1983)

\[
I_s(\theta, \lambda)/I_i = \sum_{n=1}^{\infty} I_s(\theta, \lambda)/I_i
\]

\[
= \sum_{n=1}^{\infty} \left[ \frac{n!}{n!} \tau_q^n e^{-\tau_q} \right] \left[ \frac{1}{4\pi} \sigma_0 \Phi(\theta) \right]^{*n}
\]

where \(\Phi(\theta)\) is the particle phase function and \(\sigma_0\) is the single scattering albedo (the ratio of the particle’s scattering and extinction cross-sections). \(\Phi(\theta)/4\pi\) is normalized to unity over 4\(\pi\) solid angle, and the symbol \([\cdot]^n\) denotes convolution of the term with itself \(n\) times. When \(\tau_q = \tau/\mu_0 << 1\), the \(n = 1\) term (single scattering) dominates, hence Eqs. 15.3 and 15.4 imply

\[
I_s(\theta, \lambda)/I_i \approx I_1(\theta, \lambda)/I_i = \frac{\tau e^{-\tau/\mu_0}}{4\pi \mu_0} \sigma_0 \Phi(\theta)
\]

which, when compared with Eqs. 15.1 and 15.3, defines \(\sigma_0 \Phi(\theta)\) in terms of the particle size distribution \(n(a)\) to be

\[
\sigma_0 \Phi(\theta) = \frac{\int_0^\infty \pi a^2 \left[\frac{2J_1(ka \sin \theta)}{\sin \theta}\right]^2 n(a) \, da}{\int_0^\infty \pi a^2 Q_e(a, \lambda) n(a) \, da}
\]

Terms of the infinite series in Eq. 15.4 can also be interpreted as the sum of probabilistic events. An \(n\)-th order scattering event occurs with Poisson distribution of parameter \(\tau_q\). After each interaction, the radiation is scattered (not absorbed) with probability \(\sigma_0\). After a single interaction, the probability density function of the scattered energy emerging in any given direction \(\theta\) is \(\Phi(\theta)/4\pi\). After \(n\) independent interactions, the density function is the convolution of \(\Phi(\theta)/4\pi\) with itself \(n\) times, which is denoted by the symbol \([\cdot]^n\) in the infinite sum above. This multiple scattering formulation leads to an infinite number of interactions, albeit with rapidly decreasing probability for \(n > \tau_q\).

Rings are not many particles thick (see Chapter 14), and the number of interactions as the incident radiation crosses a ring of relatively small vertical extent around the mean ring plane is likely to be limited to some upper limit \(N\). Replacing the Poisson distribution above by a binomial distribution of parameter \(p\) yields the alternative formulation (Zebker et al. 1985)

\[
I_s(\theta, \lambda)/I_i = \sum_{n=1}^{N} \left(\frac{N}{n}\right) p^n (1-p)^{N-n} \left[ \frac{1}{4\pi} \sigma_0 \Phi(\theta) \right]^{*n}
\]

where \(p\) represents the probability of a single interaction, the incident radiation emerges without any interactions with probability \((1-p)^N = \exp(-\tau_q)\), hence,

\[
p = (1 - e^{-\tau_q/N})
\]

For self-consistency, Eq. 15.1 for the classical optical depth now assumes the form

\[
\tau(\lambda) = -2\mu_0 N \ln \left[1 - \frac{1}{2\mu_0 N} \int_0^\infty \pi a^2 Q_e(a, \lambda) n(a) \, da\right]
\]

which reduces to the classical form when \(N\) is large. Although still “classical” in its basic assumptions regarding mutual particle interactions and uniform spatial distribution, the finite \(N\) model provides an additional degree
offreedom to better match the observations. The model is referred to as the thin-layers model (Zebker et al. 1985). Both the classical and the thin-layer models above allow closed form summation of the order of scattering terms in the Hankel transform domain and subsequent recovery of the single scattered component $I_s(\theta, \lambda)/I_s$ from the measured $I_r(\theta, \lambda)/I_r$, an important first step for recovery of $n(a)$ from Eq. 15.3 (see Marouf et al. 1982, 1983, Zebker et al. 1985).

15.2.2 Cassini RSS Extinction Observations

The Cassini Radio Science Subsystem (RSS) ring occultations are conducted using three simultaneously transmitted microwave frequencies. The corresponding wavelengths ($\lambda$) are 0.94, 3.6, and 13.0 cm, and the corresponding microwave bands are Ka-, X-, and S-bands, respectively. The sole ring occultation before Cassini was conducted by the Voyager 1 spacecraft in 1980 using dual-frequency (X-S; Tyler et al. 1983). As of the end of 2008, Cassini had completed 28 one-sided 3-frequency ring occultations.

The nearly pure sinusoidal signals are generated from a common ultra-stable oscillator on board Cassini (Kliore et al. 2004). The phase coherence of the signals allows measurement of the amplitude, frequency, and phase of the sinusoids after they are perturbed by ring material. Although the amplitude measurements by themselves are diffraction limited, the phase information allows reconstruction of the observations to remove diffraction effects, providing optical depth profiles of ring structure with radial resolution approaching few hundred meters (Marouf et al. 1986).

Reconstructed RSS normal optical depth ($\tau$) profiles of Rings C, B, and A are depicted in the upper panels of Figs. 15.1 a–c, respectively (Marouf et al. 2008a). The profiles are from the first Cassini diametric radio occultation (Rev 7 ingress) completed on March 3, 2005 at a ring opening angle $|B|=23.6^\circ$. The blue, green, and red profiles correspond to 0.94, 3.6, and 13.0 cm − $\lambda$ (Ka-, X-, and S-band, respectively, averaged to a radial resolution of 10 km. The lower dashed horizontal line in each panel identifies the baseline $\tau = 0$, while the upper one (when it falls within the plotted limits) identifies the optical depth level at which the measurements are noise-limited (the so-called “threshold” optical depth $\tau_{TH}$; Marouf et al. 1986). The different signal power at each frequency transmitted by Cassini, and the different noise temperature of the various groundbased receiving systems, combine to cause $\tau_{TH}$ to be wavelength dependent, as Fig. 15.1b shows, with S-band being the noisiest and X-band the least noisy profile for the same radial resolution (Marouf et al. 2008a).

As discussed above, reliable measurements of $\tau(\lambda)$ provide information about the particle size distribution $n(a)$. The normalized differential profiles $[\tau(X) - \tau(S)]/\tau(X) \equiv \Delta\tau(XS)/\tau(X)$ and $[\tau(K) - \tau(X)]/	au(X) \equiv \Delta\tau(KX)/\tau(X)$ are particularly suited to achieving this objective (Marouf et al. 1983, Zebker et al. 1985). Differential profiles corresponding to $\tau(\lambda)$ in each of the upper panels of Fig. 15.1 are shown in the corresponding lower panel. To reduce statistical scatter, the $\Delta\tau/$ profiles were smoothed to a relatively coarse resolution of 80 km. In addition, the plotted points were restricted to values 0.05 < $\tau(\lambda)$ < 3. The lower bound ensures reliably detectable $\tau(\lambda)$ and the upper one ensures $\tau(\lambda) < \tau_{TH}$ for all three signals.

Figure 15.1 reveals remarkably rich $\Delta\tau/$ variability among and within the three main ring regions: C, B, and A. A relatively large $\Delta\tau(XS)/\tau(X) \approx 30–35\%$ characterizes almost the full extent of the tenuous background structure of Ring C, with possibly systematic decreasing trend as radius increases. Deviations from the background values within the denser “plateaus” in the outer C ring are likely to be real (~86,000–90,600 km). Different $\tau(\lambda)$ variations are evident within individual dense ringlets in the upper panel of Fig. 15.1a. Voyager X-S observations indicated similar behavior, albeit at coarser radial resolution (Tyler et al. 1983). Clearly detectable $\Delta\tau(KX)/\tau(X)$ approaching 10% characterizes the tenuous wavy region in mid Ring C (~78,000 to 86,000 km). Little mean $\Delta\tau(KX)/\tau(X)$ is evident over the plateau region (84,500–90,500 km). Although the $\tau(\lambda)$ profiles of the outer Ring C ramp (~90,600 to 92,000 km) show systematically increasing $\Delta\tau(KX)$ and $\Delta\tau(XS)$ with radius, when normalized by the also increasing $\tau(X)$ with radius, the normalized differential has nearly constant $\Delta\tau(KX)/\tau(X) \approx 9\%$ and $\Delta\tau(XS)/\tau(X) \approx 30\%$.

Much less evident differential extinction of the three radio signals characterizes two of the four main regions of Ring B, provisionally identified as regions B1 to B4 (Marouf et al. 2008a). As Fig. 15.1b shows, the two are regions B2 (~99,000–104,100 km) and B4 (~110,000–117,500 km). Region B3 (~104,100–110,000 km; the “core” of Ring B) yields mostly noise-limited measurements at all three frequencies (except for a few narrow “lanes” of smaller optical depth). In sharp contrast, the innermost region of Ring B, region B1 (~92,000–99,000 km), exhibits clearly detectable $\Delta\tau(XS)/\tau(X)$ over most of its extent, including the two relatively “flat” features evident in the upper panel of Fig. 15.1b. An estimated $\Delta\tau(XS)/\tau(X)$ of ~20% across both flat features is distinctly smaller than typical values across most of Ring C. Marginally detectable $\Delta\tau(KX)/\tau(X)$ of a few percent characterizes the wider of the two flat regions, with little or no Ka-X differential detectable elsewhere.

Differential optical depth profiles of Ring A (Fig. 15.1c) present their own distinct behavior. Like Rings B2 and B4, small or no X-S or Ka-X differential is detectable over the relatively optically thick inner region neighboring the
Fig. 15.1  (a) Upper panel: Cassini Radio Science Subsystem (RSS) normal optical depth profiles of Ring C observed at the three microwave wavelengths (bands) indicated. The profiles were observed during the Rev 7 ingress ring occultation on March 3, 2005, at ring opening angle $|B| = -23.6^\circ$. The normal value is the measured oblique value scaled by $\sin(|B|)$. The radial resolution is $\Delta R = 10$ km. Lower Panel: The corresponding normalized X-S (red) and Ka-X (blue) differential optical depth. The radial resolution is degraded to $\Delta R = 80$ km to reduce scatter. The plotted differential is limited to regions of normal optical depth $>0.05$ and $<3.5$ to ensure reliability. (Marouf et al. 2008a).  
(b) Same as Figure 1a but for Ring B. The three dashed horizontal lines in the upper panel identify the optical depth level at which the measurement signal-to-noise ratio (SNR) drops to $\sim 1$ (the threshold optical depth). The different threshold values reflect the different intrinsic free-space SNR for the Ka-, X-, and S-band signals (blue, green, and red lines, respectively). B1, B2, B3, and B4 identify four main regions of Ring B bounded by the approximate radius values 92,000, 99,000, 104,100, 110,000, 117,500 km. The measurements are noise limited in region B3 (the “core” of Ring B), except for few narrow “lanes.” (Marouf et al. 2008a).  
(c) Same as Figure 1a but for the Cassini Division and Ring A. Detailed differential profiles for the Cassini Division region interior to the outer ramp feature require careful calibration of the free-space signals level and are still to be determined (Marouf et al. 2008a)
outer ramp of the Cassini Division. Over the ~6,500 km wide inner region of Ring A (~122,500–129,000), \( \Delta \tau(XS)/\tau(X) \) increases by no more than a few percent, while \( \Delta \tau(KX)/\tau(X) \) remains close to zero. Unlike the observed behavior in Rings B or C, a gradual, and significant, increase in the X-S differential characterizes the outer ~7,800 km region of Ring A (~129,000–136,800 km). The rate of increase is largest over the region inside the inner boundary of the Encke Gap (roughly at 133,500 km) where the X-S differential reaches ~20%. As Fig. 15.1c illustrates, enhancements in \( \Delta \tau(XS)/\tau(X) \) over the background level are also evident within some major wave features.

The Ka-X differential, on the other hand, remains small or absent over most of the extent of Ring A, exhibiting occasional negative, albeit small, values over the radius region outside ~130,000 km. The exception is the narrow band between the Keeler Gap and the outer edge of the rings, where a relatively large Ka-X differential of ~10% is observed. The band is also distinguished by exhibiting the largest X-S differential observed in Ring A (40%). The large differentials are reminiscent of values observed in Ring C.

Not discussed in comparable detail here is the Cassini Division (117,500–122,500 km roughly). Reliable characterization of the differential behavior of small optical depth features requires careful calibration of the free-space baseline. Nonetheless, we point out the remarkable similarity between the behavior of the \( \tau(\lambda) \) profiles of the outer ramp of the Cassini Division (at ~121,500 km) and that of Ring C (at ~91,300 km; Figs. 15.1a and c). Despite the morphological similarity in \( \tau(\lambda) \), the behavior of the \( \Delta \tau(XS)/\tau(X) \) profiles appear different for the two features, being nearly constant across the Ring C ramp and increasing with increasing radius for the Cassini Division ramp. For both ramp features, \( \Delta \tau(KX)/\tau(X) \) appears nearly constant across the feature’s width.

### 15.2.3 Model Results

Assuming a classical ring model, the observed \( \Delta \tau(XS)/\tau(X) \) and \( \Delta \tau(KX)/\tau(X) \) may be used to constrain parameters of an assumed power-law particle size distribution \( n(a) \), as discussed above. Starting from Eq. 15.1, the dependence of \( \tau(\lambda) \) on wavelength \( \lambda \) is attributed to the behavior of the extinction efficiency \( Q_e(a,\lambda) \). In particular, the strong dependence of \( Q_e(a,\lambda) \) on wavelength for \( 2\pi a/\lambda < 1 \) (van de Hulst 1957; Tyler et al. 1983, Fig. 6; Marouf et al. 2008a) is the physical mechanism responsible for the measured differentials depicted in Fig. 15.1. Model values of \( \Delta \tau(XS)/\tau(X) \) and \( \Delta \tau(KX)/\tau(X) \), computed using Eq. 15.1, depend on the differential \( Q_e \) averaged over \( n(a) \), and hence on \( a_{\text{min}}, a_{\text{max}}, \) and \( q \) of the assumed power-law size distribution (see Eqs. 15.2 and 15.2). The ratio eliminates dependence on \( n_0 \) (see Marouf et al. 2008a for details).

Predicted differentials, based on model calculations of this type, may be directly compared with actual
measurements for selected ring features. The comparison is carried out for seven of the eight features identified in Fig. 15.2. The feature extent is identified by the dashed vertical lines. For brevity, the features are referred to below as mid-C, C-ramp, B1-flat, in-B2, in-B4, inner-A, and outer-A. The Cassini Division ramp is included in Fig. 15.2 for profile comparison with the C-ramp but is not included in the model matching analysis below.

Figure 15.3 depicts results of the comparison for both the classical and thin layer ($N = 1, 2, 3$ and $4$) ring models. The two independent measurements $\Delta \tau(KX)/\tau(X)$ and $\Delta \tau(XS)/\tau(X)$ define the two orthogonal axes, and the set of measured sample points for a given feature define a cluster in this measurements plane. The seven clusters shown correspond to seven of the features in Fig. 15.2, as labeled. Superposed are power-law model predictions spanning a range of $(a_{\min}, a_{\max}, q)$. For a given $q$, the predicted $\Delta \tau(KX)/\tau(X)$ and $\Delta \tau(XS)/\tau(X)$ are plotted as a continuous curve parameterized by $a_{\min}$. Results for $a_{\min} = 1, 3, 5$ mm, 1, 3, 10 cm, and 1 m are explicitly labeled. For each $q$, results for $a_{\max} = 3$ and 10 m are shown.

The model and results in Fig. 15.3 have three important implications. The first is that for $q > ~2.8$, a detectable $\Delta \tau(XS)/\tau(X)$ provides a direct estimate of $q$ if $a_{\min} < ~1$ cm. The larger the observed differential, the larger the implied $q$. For the mid-C, C-ramp, and outer-A features, where $\Delta \tau(XS)/\tau(X) ~ 30–35\%$, the implied $q$ is $~3.2–3.3$, in agreement with the Voyager results for the assumed classical model (Marouf et al. 1982). The smaller $\sim 20\%$ differential for the B1-flat feature implies a smaller $q ~ 3.1$, a new result (Ring B was mostly noise limited in the Voyager case). In general, the inferred $q$ is somewhat smaller if the thin layer model is assumed instead, dropping for the B1-flat feature to $q = ~3$ for $N = 2$ to 4.

The second important implication of results in Fig. 15.3 is that, for $q > ~2.8$, simultaneous measurement of $\Delta \tau(KX)/\tau(X)$ and $\Delta \tau(KX)/\tau(X)$ also determine or constrain $a_{\min}$, a unique Cassini capability. In particular, for $a_{\min} < ~1$ cm, $\Delta \tau(KX)/\tau(X)$ uniquely determines $a_{\min}$, independently of the model assumed. In the case of the mid-C and the C-ramp features, a $\Delta \tau(KX)/\tau(X) ~ 10\%$ implies $a_{\min} ~ 4$ mm; the few percent differential in the outer-A and the B-flat features imply $a_{\min} ~ 5$ mm. The implied lower cutoff is sharp. Further numerical simulations suggest that the cutoff need not be an actual sudden drop in the particle number density to very small values, and can be relative flattening of the distribution to values $q < ~2.7$ over $a < ~4$ mm.

The third important implication of results in Fig. 15.3 is that, for either the classical or thin layers ring models, small or undetectable X-S and Ka-X differential, as is the case for the two Ring B features (in-B2 and in-B4) and the inner-A features, can be due to either a true absence of particles smaller than $\sim 50$ cm in radius or a still broad distribution with $q < ~2.7$. In the latter case, the relative abundance of the millimeter- to decimeter- size particles that differentially
Fig. 15.3 (Left) Comparison of the measured X-S (vertical axis) and Ka-X (horizontal axis) differential optical depth with predictions of a power-law size distribution model of the indicated parameters. For a given power-law index \( q \), the predicted differentials are plotted using the minimum radius \( a_{\text{min}} \) as a parameter. Points \( a_{\text{min}} = 0.1, 0.3, 0.5, 1, 3, 10, \) and 100 cm are as identified. For each case, dependence on \( a_{\text{max}} \) is illustrated for the two cases \( a_{\text{max}} = 3 \) (solid blue) and 10 m (dashed red). The seven clusters are the values measured for seven of the ring features identified in Figure 3, as labeled. Individual points within each cluster are 80 km resolution samples. The comparison is based on the assumption of a classical (many-particle-thick) ring model. (right) Same figure, except that the measured values are scaled based on the thin layers ring model. The five points for each feature correspond to number of layers fours \( N = 1 \) to 4 and the classical model result 'c', as labeled. Each point is an average over the radial width of the corresponding ring feature (Marouf et al. 2008a)

features identified in Figure 3, as labeled. Individual points within each cluster are 80 km resolution samples. The comparison is based on the assumption of a classical (many-particle-thick) ring model. (right) Same figure, except that the measured values are scaled based on the thin layers ring model. The five points for each feature correspond to number of layers fours \( N = 1 \) to 4 and the classical model result 'c', as labeled. Each point is an average over the radial width of the corresponding ring feature (Marouf et al. 2008a)

affect the three radio wavelengths remains too small to cause any detectable effect.

As Fig. 15.3 also illustrates, the results described above are relatively insensitive to the exact upper bound of the size distribution \( a_{\text{max}} \), a parameter better determined or constrained by near-forward scattering observations. We note here that limits on \( a_{\text{min}} \) can also be placed by the scattering observations at wavelengths for which \( k a_{\text{min}} \gg 1 \), and hence all particles are large compared with the wavelength (see Section 15.2.6). We discuss inferences of \( a_{\text{max}} \) from scattered signal observations below.

15.2.4 Near-Forward Scattered Signal Observations

In radio and stellar occultations, the signal power lost from the electromagnetic radiation passing straight through the rings (the direct signal or direct flux) is either absorbed by ring particles and/or scattered into other spatial directions. Absorption is negligible if the absorption coefficient (or imaginary refractive index) of ring particles is small at the observational wavelength. For the near-forward occultation geometry, the scattered signal component is dominated by diffraction by particles large compared to the wavelength \( (ka \gg 1) \). Eq. 15.3 may then be used to recover \( n(a) \) over the radius range \( a > a_c \). The exact size range depends on the wavelength of the observations, but is typically \( a > \sim 1 \) cm for stellar occultations (French and Nicholson 2000), and \( a > \sim 1 \) m for radio occultations (Marouf et al. 1983).

In both types of occultations, separation of the contributions of the direct and scattered signals requires special effort. In the case of radio occultations, the coherent nature of the incident radiation allows the separation based on the distinct spectral nature of each component (Marouf et al. 1982; Thomson et al. 2007). In stellar occultations, the spacecraft radio transmitter is replaced by a distant star and the Earth-based receiver is replaced by a spacecraft-based detector. Because the incident stellar flux is incoherent in nature, the direct and scattered flux components cannot be separated based on their spectral properties and other approaches are required (Section 15.2.6).

The schematic of the idealized occultation observation shown in Fig. 15.4 illustrates the conditions. Normal incidence is assumed for simplicity. A detector at distance \( D \) from the rings, modeled for example as a circular aperture of radius \( a_{\text{ap}} \), has an acceptance or resolution angle \( \theta_{\text{ap}} \sim \lambda/2a_{\text{ap}} \). Particles of radius \( a > a_{\text{ap}} \) will diffract the incident signal over an angle \( \theta_1 = \lambda/2a < \theta_{\text{ap}} \), and the field of view of the detector on the ring plane (the circle of radius \( \theta_{\text{ap}}D \) in Fig. 15.4) will encompass the diffraction
transmitted signal emerges after scattering from particles in the detected zone of scatterers (the zone within \( \theta_a D \)) with a Doppler-shifted frequency that depends on its location in the zone, spectral analysis can refine the spatial resolution to regions smaller than \( \theta_a D \), especially useful if the Doppler contours are aligned with lines of constant ring radius (see Marouf et al. 1982, 1983, Zebker et al. 1985, and Marouf et al. 2008a for details).

It is well known that a particle of radius \( a \) large compared to the wavelength \((ka >> 1)\) removes from the incident wave exactly twice the amount of light it intercepts (van de Hulst 1957). In that case, the extinction cross section \( C_e = 2\pi a^2 \) and the extinction efficiency \( Q_e = C_e/\pi a^2 = 2 \). Exactly half of the power per unit area lost from the incident signal is accounted for by the total power in the diffraction pattern. If the diffraction lobe is fully captured by the detector, the apparent extinction efficiency \( Q_e \) drops from 2 to 1 (see, e.g., Cuzzi 1985). Thus, in an occultation for which the condition \( ka >> 1 \) holds for all ring particles of radius \( a > a_c \), the observed normal optical depth reduces to the geometric optical depth, defined as

\[
\tau_e = \int_{a_c}^{\infty} \pi a^2 n(a) \, da \quad (15.10)
\]

Figure 15.4 also helps illustrate the limit on the smallest particle radius that contributes to the shape of the rings’ collective diffraction lobe. In the radio case, the spacecraft high-gain antenna (HGA) plays the role of the detector in the stellar case (because its illumination selects the sampled area on the rings), and the HGA beamwidth plays the role of the detector acceptance angle \( \theta_{ap} \). Particles of radius \( a \) satisfying \( \theta_a D > \theta_{ap} D \) scatter nearly isotropically over \( \theta_{ap} \), hence contributing little or no information regarding the shape of the collective diffraction pattern. Only particles of size comparable to or larger than the antenna meaningfully contribute to any observed angular variations. Both Voyager and Cassini use a 2 m radius dish, setting the limit \( a > ~1 \text{ m} \) in the radio occultation case (Marouf et al. 1982, 1983; Zebker et al. 1985). The limit is much smaller in the stellar occultation case, e.g., \( a > ~4 \text{ cm} \) for \( \lambda = 1 \mu m \) and \( a > ~15 \text{ cm} \) for \( \lambda = 4 \mu m \) (French and Nicholson 2000).

### 15.2.5 Size Distribution from the Voyager RSS Observations

The Voyager 1 radio occultation in 1980 provided the first definitive detection of near-forward scattered X-band signal in the time sequence of observed spectra (Tyler et al. 1983, Marouf et al. 1983). The small ring-opening angle at the time \((B = 5.9^o)\) caused the Voyager antenna beam to sample a
relatively large ring area at any given observation time. The experiment geometry was optimized to closely align contours of constant Doppler-shift with contours of constant ring radius. Both the scattered signal observations and the X-S differential extinction observations were used to determine self-consistent size distributions for several main ring features, including mid Ring C, Ring C ramp, Cassini Division ramp, inner Ring A, and outer Ring A (Marouf et al. 1983, Zebker et al. 1985). The features are similar to, but not identical, to those in Fig. 15.2; see Table 15.1 for exact definitions. Voyager measurements in Ring B were largely noise-limited.

Assuming the classical model, Marouf et al. (1983) recovered the first explicit size distribution of ring particles over the radius range 1 < a < 15 m for four main ring features (Fig. 15.5, Table 15.1). The distributions revealed a sharp upper size cutoff in the 3–5 m radius range, depending on the feature. Knowledge of n(a), a > 1 m, allows computing the contribution of particles in this radius interval to the measured X- and S-band optical depth, constraining the adjusted optical depth due to smaller particles. Modeling the distribution over a < 1 m by a power-law having a_{min} small enough to contribute negligibly (a_{min} = 1 cm) and a_{max} = 1 m, the index q follows from the differential Δτ(XS)/τ(X) and the scaling factor n₀ follows from τ(X), both computed over the limited range 1 cm < a < 1 m. The combined power-law model and the explicit inversion results yielded the first detailed characterization of n(a) over the broad range 1 cm < a < 15 m, for the three optically thin features in Fig. 15.5 (Marouf et al. 1983); see also Table 15.1.

Figure 15.5 illustrates a problem with the classical model assumed. Estimated q = 3.5, 3.4, and 3.3 for features C1.35, C1.51, and CD2.01 (the red lines in Fig. 15.5; Table 15.1) yield n(a) values that connect poorly with the explicit inversion over a > ∼1 m. Overcompensating for multiple scattering effects in recovering n(a) from I_s(θ, λ) would cause an overestimate of the absolute n(a) values recovered over a > 1 m, hence the mismatch near a = 1 m. The thin-layers model (see Section 15.2.1) controls the contribution of multiple scattering to I_s(θ, λ) and constrains values of the number of layers N that yield self-consistent results near a ∼ 1 m. Results for the three features in Fig. 15.5 and others in Ring A are shown in Fig. 15.6 (Zebker et al. 1985). Less steep (smaller) q’s over 1 cm < a < 1 m are implied in this case; see Table 15.1. The more self-consistent matching of the power-law with the upper-size cutoff results suggests that the finite-thickness models are a better fit to reality, consistent with dynamical expectations (see Chapters 13 and 14).

### Table 15.1 Particle Size Distribution from Radio and Stellar Occultations of Saturn’s Rings

<table>
<thead>
<tr>
<th>Ring region</th>
<th>Radius Range (km)</th>
<th>q</th>
<th>a_{min} (cm)</th>
<th>a_{max} (m)</th>
<th>n₀(1 cm) (#/m²/m)</th>
<th>Q</th>
<th>a_{eff}(PPS) (m)</th>
<th>a_{eff}(RSS) (m)</th>
<th>a_{eff}(28 Sgr) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voyager RSS(^{(a)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1.35</td>
<td>78,430–84,460</td>
<td>3.11</td>
<td>0.1</td>
<td>4.5</td>
<td>2700</td>
<td>0.0028</td>
<td>1.4</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>C1.51</td>
<td>90,640–91,970</td>
<td>3.05</td>
<td>0.1</td>
<td>2.4–5.3</td>
<td>2990</td>
<td>0.0086</td>
<td>2.3</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>CD2.01</td>
<td>120,910–122,010</td>
<td>2.79</td>
<td>0.1</td>
<td>7.5</td>
<td>1780</td>
<td>0.026</td>
<td>3.9</td>
<td>2.44</td>
<td></td>
</tr>
<tr>
<td>A2.10</td>
<td>125,490–127,900</td>
<td>2.70</td>
<td>0.1</td>
<td>5.4</td>
<td>3300</td>
<td>0.242</td>
<td>11.6</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>A2.12</td>
<td>125,490–130,310</td>
<td>2.74</td>
<td>0.1</td>
<td>5.0</td>
<td>2870</td>
<td>0.26</td>
<td>11.9</td>
<td>1.65</td>
<td></td>
</tr>
<tr>
<td>A2.14</td>
<td>127,900–130,310</td>
<td>2.75</td>
<td>0.1</td>
<td>6.3</td>
<td>3530</td>
<td>0.262</td>
<td>11.2</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>A2.19</td>
<td>130,860–133,270</td>
<td>2.93</td>
<td>0.1</td>
<td>11.2</td>
<td>5650</td>
<td>0.252</td>
<td>11.2</td>
<td>1.82</td>
<td></td>
</tr>
<tr>
<td>A2.24</td>
<td>133,930–136,350</td>
<td>3.03</td>
<td>0.1</td>
<td>8.9</td>
<td>8950</td>
<td>0.18</td>
<td>9.6</td>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td>Earth-Based 28 Sgr(^{(b)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring C</td>
<td>74,490–91,983</td>
<td>3.1</td>
<td>1</td>
<td>10</td>
<td>&lt;0.002–0.012</td>
<td>&lt;1.2–2.8</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring B</td>
<td>91,183–117,516</td>
<td>2.75</td>
<td>30</td>
<td>20</td>
<td>0.05–0.12</td>
<td>5.7–8.8</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cassini Division</td>
<td>117,516–122,053</td>
<td>2.75</td>
<td>0.1</td>
<td>20</td>
<td>&lt;0.002–0.035</td>
<td>&lt;1.1–4.5</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner Ring A</td>
<td>122,053–133,423</td>
<td>2.75</td>
<td>30</td>
<td>20</td>
<td>0.23–0.27</td>
<td>11.2–12.2</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Ring A</td>
<td>133,745–136,774</td>
<td>2.9</td>
<td>1</td>
<td>20</td>
<td>0.16–0.16</td>
<td>9–10.7</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{(a)}\) Size distribution from the Voyager radio occultation observation (Zebker et al., 1985). The distribution parameters are inferred from inversion of the near-forward scattered 3.6 cm − λ (X-band) signal over a > 1 m and modeling of the 3.6 and 13 cm − λ (S-band) differential extinction as a power-law distribution over 0.1 cm < a < 1 m. A minimum radius a_{min} = 0.1 cm is assumed for all ring regions. The results are based on the thin-layers ring model (see Section 15.2.1).

\(^{(b)}\) Size distribution from the Earth-based 28 Sgr stellar occultation (French and Nicholson, 2000). The distribution parameters are inferred from comparison of the strength and shape of profiles of the observed near-forward scattered stellar flux at 0.9, 2.1, and 3.9 μm wavelengths with theoretical predictions based on a power-law size distribution model. The model parameters are assumed uniform across each main ring region and are selected to provide a compromise match to data at all three wavelengths. Results for the Cassini Division are not well determined. The results are based on the classical ring model.

\(^{(c)}\) Effective radius from the variance of the statistical fluctuations in photon count observed during the Voyager PPS stellar occultation (Showalter and Nicholson, 1990). The parameter Q characterizes the increase in variance above Poisson count statistics. It provides an estimate of the effective particle radius a_{eff}(PPS) which is controlled by the 4th moment of the size distribution. For comparison purposes, the last two columns also list a_{eff} computed based on the inferred RSS and 28 Sgr size distributions (French and Nicholson, 2000, Showalter and Nicholson, 1990). The results are based on the classical ring model.
15.2.6 Size Distribution from 28 Sgr Stellar Occultations

The 1989 stellar occultation of 28 Sgr by the Saturn system was widely observed, and provided the first detailed post-Voyager examination of the geometry, structure and scattering properties of Saturn’s rings. This occultation was unique in that the star was unusually bright, and its diminished signal could be detected even on top of sunlight reflected from the rings. The observed intensities were a complicated blend of directly attenuated starlight and starlight diffracted into the detector from other regions of the rings. French and Nicholson (2000) used ring occultation profiles from the Lick ($\lambda = 0.9\mu m$), McDonald ($\lambda = 2.1\mu m$), and Palomar ($\lambda = 2.1\mu m$) observatories to infer the size distribution of the ring particles. The Voyager PPS optical depth profile was used to estimate and remove the direct signal contribution to the observed total flux, and the method concentrated on interpreting the diffracted signal.

For the idealized geometry of Fig. 15.4, an Earth-based detector of acceptance angle $\theta_{ap}$ looking back at the rings at distance $D$ collects the superposition of contributions from all ring elements at angles $\theta$ within its field of view. Assuming single scattering, the intensity of the diffracted light $I_1(\theta, \lambda)$ is governed by Eq. 15.5. The total scattered flux was modeled by a two dimensional convolution, for the exact 28 Sgr observation geometry, constraining an assumed power-law size distribution parameters to achieve a good match to the measured flux. The power-law parameters were fit separately for
each main ring region. The piecewise best solutions are then used collectively to compute a predicted composite scattered signal for the entire ring system. Table 15.1 lists the compromise power-law model parameters for each ring region that gave the best overall fit to the observations at all three observation wavelengths.

### 15.2.7 Size Information from the Excess Variance in Stellar Occultations

This is a fundamentally different approach to constraining ring particle sizes using stellar occultation measurements (Showalter and Nicholson 1990). It stipulates that the statistical fluctuations in the photon count \( k \) (not to be confused with the wavenumber \( k \) used earlier) measured by the photodetector behind the rings are partly intrinsic and partly due to the random nature of the local ring area blocking the incident stellar flux. The intrinsic part originates in the stochastic nature of the incident stellar photon count (\( S \)) and any background contribution (\( B \)), for example from Saturnshine. Both intrinsic components are well modeled by Poisson distributions of parameters \( \lambda_2 \) and \( \lambda_B \). The expected value \( E(k) \) during occultation by a ring region of oblique optical depth \( \tau/\mu_0 \) is

\[
E(k) = \lambda_S e^{-\tau/\mu_0} + \lambda_B = \lambda_S P + \lambda_B
\]  

(15.11)

where \( P = \exp(-\tau/\mu_0) \) is the fraction of ring area not blocked by ring particles and \( \tau \) accounts for whatever role near-forward diffraction plays (Section 15.2.4).

Showalter and Nicholson (1990) argue that independent additional information about particle sizes is provided by the higher order statistical averages of the photon count \( k \), in particular, its variance \( \sigma^2(k) \). Ring particles large enough to stochastically perturb the fraction of ring area not covered (\( P \)) would introduce additional stochastic fluctuations in \( k \), hence contribute to \( \sigma^2(k) \). Treating \( P \) as a random variable of mean \( \exp(-\tau/\mu_0) \) and variance \( \sigma^2(P) \), they show that

\[
\sigma^2(k) = E(k) + \lambda_2^2 \sigma^2(P)
\]  

(15.12)

The first term is the variance if \( P \) were deterministic, and the second is the “excess variance,” that is, the additional contribution to \( \sigma^2(k) \) due to “ring noise”, which is a measure of the variation in blockage fraction of the sampled patch of local ring material. The effective area contributing to the direct signal, \( A_\text{eff} \), depends on the size of the first Fresnel zone smeared by the motion of the spacecraft. The effective area contributing to the scattered signal, \( A_s \), is determined by the detector field of view (the circle of radius \( \theta_D D \) in Fig. 15.4 adjusted for oblique incidence). In addition to dependence on \( A_d \) and \( A_s \), \( \sigma^2(k) \) is strongly controlled by a dimensionless parameter \( Q \) (not to be confused with the extinction efficiency \( Q_e \) defined as

\[
Q = \frac{\int (\pi a^2)^2 n(a) da}{\mu_0 A_d} \frac{\int \pi a^2 n(a) da}{\mu_0 A_d} = \frac{\pi a_{\text{eff}}^2}{\mu_0 A_d}
\]  

(15.13)

where \( Q \) can iteratively be estimated from the observed time series \( k \) measured during the Voyager PPS occultation, and

\[
a_{\text{eff}} = \sqrt{\frac{\int a^4 n(a) da}{\int a^2 n(a) da}}
\]  

(15.14)

Hence, \( a_{\text{eff}} \) is strongly weighted toward the largest particle sizes and the \( Q \)-profiles provide constraints on the largest particle sizes across the main ring regions with achievable radial resolution as fine as 20 km. \( Q \)-profiles of Rings C, B, and A are shown in Fig. 15.7; see Table 15.1 for translation of these \( Q \) values into particle radii.

### 15.2.8 Summary of Current Knowledge and Limitations

Table 15.1 groups comparative results from the Voyager radio occultation, the 28 Sgr stellar occultations, and the Voyager PPS excess variance observations. The table is adapted from similar tables in Zebker et al. (1985), Showalter and Nicholson (1990), and French and Nicholson (2000). More recent Cassini results were presented in Figs. 15.1 and 15.3 (Marouf et al. 2008a).

The upper left side of Table 15.1 lists \((q, a_{\text{max}}, n_0)\) of a power-law model (Eq. 15.2) consistent with the direct and near-forward scattered (diffracted) signals observed during the Voyager radio occultation. The Voyager observations did not constrain \( a_{\text{min}} \), which was assumed to be much less than the \( \lambda = 3.6 \) cm wavelength of the X-band signal (\( a_{\text{min}} = 0.1 \) cm). Results for eight ring features and their radial extent are tabulated.

Similar results for the 28 Sgr occultation are listed in the lower left part of the table. Here, parameters \((q, a_{\text{min}}, a_{\text{max}})\) are constrained by the estimated near-forward scattered flux shape and strength. Before Cassini, the 28 Sgr results provided the only available direct constraints on \( a_{\text{min}} \). Cassini radio occultation observation of the Ka-X differential optical depth (Figs. 15.1 and 15.3) provide new tight constraints on \( a_{\text{min}} \). Except for Ring A, the 28 Sgr results are assumed to uniformly apply to each of Ring C, Ring B, and the Cassini Division as a whole. Results for inner (interior to the Encke Gap) and outer (between the Encke and Keeler Gaps) regions of Ring A are inferred independently (Table 15.1).
The last four columns of Table 15.1 list results based on the $Q$-parameter from the PPS excess variance observations. The first of these lists $Q$ itself and the second the implied $a_{\text{eff}}$, denoted $a_{\text{eff}}(\text{PPS})$ to emphasize its inference from the PPS data. The third column lists $a_{\text{eff}}(\text{RSS})$ implied by Eq. (15.14) if the size distribution $n(a)$ is assumed to be a power-law of the same parameters determined by the radio occultation observations of the corresponding feature (values are in Showalter and Nicholson 1990). The last column, $a_{\text{eff}}(28\text{Sgr})$, is the same except that $n(a)$ is determined by the 28 Sgr occultation (values are from French and Nicholson 2000).

### 15.2.9 Comparison of the Four Main Ring Regions

Overall the particle sizes in the main rings seem to follow powerlaw distributions in radius of the form $n(r, r + dr) = n_0 r^{-q} dr$, where the slope $q$ of the powerlaw, and the upper and lower radius limits, vary with location in the rings. Generally speaking $q \sim 3$, suggesting there is equal surface area per decade and most of the mass is in the larger particles, the lower radius limit is in the 1–30 cm range, and the upper radius limit is in the 2–20 m range. More detailed discussion is given below.

**Ring C:** Both the Voyager radio and the 28 Sgr stellar occultations suggest a relatively steep power-law index $q \sim 3.1$ in Ring C. The Cassini Ka-X differential optical depth suggests slightly steeper $q \sim 3.2$ and strongly constrains $a_{\text{min}}$ to be $\sim 4$ mm (Fig. 15.3), in general agreement with $a_{\text{min}} = 1$ cm from the 28 Sgr observations (Table 15.1). A largest particle radius $a_{\text{max}} = 4.5$ m in mid ring C and $\sim 2.5–4.5$ m in the Ring C ramp from the Voyager radio occultation is smaller than $a_{\text{max}} = 10$ m from the stellar occultation over the full Ring C. The inferred values are still within an estimated factor of 2 to 3 uncertainty in the latter, however. Both the 28 Sgr occultation and the excess variance ($Q$-based) result imply similar $a_{\text{eff}} \sim 2.3$ m, and hence similar $a_{\text{max}}$. An estimated $Q$ increasing with radius over the Ring C ramp (Fig. 15.7a) suggests an $a_{\text{max}}$ increasing with radius across this feature. Cassini Ka-X and X-S differential optical profiles (Fig. 15.1a) show no evidence for significant variations in $q$ or $a_{\text{min}}$ across the Ring C ramp feature (Fig. 15.3).

**Ring B:** The Voyager radio occultation observation of Ring B was mostly noise limited, since the rings were nearly closed at the time ($B = 5.9^\circ$); not so for Cassini at much larger $B$. The differential X-S and Ka-X optical depth Cassini observations suggest a size distribution for the innermost region of Ring B (region B1) that is different from the other three regions (B2, B3, and B4; Fig. 15.1b). In particular, the nearly flat feature between $\sim 94,400$ and 95,300 km is characterized by a $q \sim 3–3.1$ and $a_{\text{min}} \sim 4$ mm (Fig. 15.3;
Regions B2 and B4 show little detectable X-S or Ka-X differential, indicating either relatively large $a_{\min} > \sim 50$ cm or relatively flat power law index $q < \sim 2.7$. Clearly detectable $Q$-values over region B1 (Fig. 15.7) imply an $a_{\text{eff}}$ (PPS) = 5.7 m within the flat feature, and a larger $a_{\text{eff}}$ (PPS) = 8.8 m on either side of the feature (Table 15.1). No reliable $Q$-based estimates of $a_{\text{eff}}$ are available for other regions of Ring B. For the 28 Sgr case, a single uniform size distribution for regions B1, B2, and B4 has parameters $q = 2.75$, $a_{\min} = 30$ cm, and $a_{\max} = 20$ m (Table 15.1). Comparison with the more localized estimates above must be regarded with due care. An implied $a_{\text{eff}}$ (28 Sgr) = 8.3 m appears consistent with the $Q$-based estimate of 5.7–8.8 m in region B1, and an $a_{\min} = 30$ cm is more or less consistent with the Cassini radio inference of $a_{\min} > 50$ cm as one potential reason for the lack of observed X-S-Ka differential in regions B2 and B4. Region B3 is noise limited in all observation types.

**Cassini Division:** The size distribution from the Voyager radio occultation is limited to the outer Cassini Division ramp feature, where the estimated $q < 2.79$ and $a_{\max} = 7.5$ m are also comparable to their values in the inner A Ring (Table 15.1). The Cassini X-S differential optical depth exhibits a systematic increase with radius (Fig. 15.1c), suggesting that the size distribution may be varying across the 1,100 km extent of this feature. A similar systematic increase in estimated $Q$ with radius (Fig. 15.7c and d) suggests that $a_{\max}$ may be increasing with increasing radius. A mean $a_{\text{eff}}$ (PPS) = 3.9 m for the ramp feature is larger by a factor of 2 than $a_{\text{eff}}$ (RSS) = 2.4 m from the Voyager RSS size distribution, and smaller by the same factor than $a_{\text{eff}}$ (28 Sgr) = 7 m from the 28 Sgr size distribution. Smaller estimated $Q$ values for the tenuous Cassini Division region interior to the ramp imply smaller $a_{\text{eff}}$ (PPS) = 1.1 m, hence smaller $a_{\max}$. Because of its relative narrowness (4,500 km wide), the size distribution from the 28 Sgr occultation is not well determined in this ring region. Nonetheless, inferred $q = 2.75$ and $a_{\max} = 20$ m are in general agreement with inferences in the neighboring inner A Ring (Table 15.1).

**Ring A:** Both Voyager and Cassini radio occultations reveal interesting X-S differential optical depth that increases with increasing ring radius (Tyler et al. 1983, Marouf et al. 2008a; Fig. 15.1c). The X-S differential increase could be explained by either an increasing $q$ or a decreasing $a_{\min}$ with increasing ring radius. A small observed Ka-X differential suggests that the increasing X-S differential over mid and outer Ring A is likely due to an increasing $q$. An exception perhaps is the outermost region between the Keeler Gap and the outer edge of Ring A, where the Ka-X differential is not small. Inferences from the Voyager radio occultation suggest an increase of $q$ from about 2.7 in inner and mid Ring A to about 3 in the neighborhood of the Encke Gap. The estimated $a_{\max}$ also appears to increase from about 5–6 m to about 9–11 m in these two regions (Table 15.1).

Estimates from the 28 Sgr stellar occultation yield $q = \sim 2.75$, $a_{\min} = 30$ cm, and $a_{\max} = 20$ m in the inner and mid Ring A region (interior to the Encke Gap), and $q = \sim 2.9$, $a_{\min} = 1$ cm, and $a_{\max} = 20$ m in the outer region (between the Encke and Keeler Gaps). The $q$ values and the trend are consistent with the Voyager radio estimates, and somewhat smaller than a Cassini radio estimate of $q = \sim 3.15–3.2$ (Fig. 15.3). A large $a_{\min} = 20$ cm in the inner region is compatible with the observed small X-S-Ka differential optical depth in the innermost part of Ring A but is difficult to reconcile with regions closer to the Encke gap where a relatively large X-S differential is observed. On the other hand, an $a_{\min} = 1$ cm in outer Ring A is compatible with the Cassini radio observations where $a_{\min} = 4–5$ mm is inferred (Fig. 15.3). It’s likely that the size distribution varies continuously across Ring A. The 28 Sgr estimate of $a_{\max} = 20$ m in both inner and outer Ring A is a factor of 2 to 4 larger than the radio values (Table 15.1). A large $a_{\max}$ is also suggested by the $Q$-based estimates of $a_{\text{eff}}$ (RSS) = 9.6 to 11.6 m, in general agreement of $a_{\text{eff}}$ (28 Sgr) = 6 to 8.3 m from the 28 Sgr inferred size distributions. Both estimates are much larger than $a_{\text{eff}}$ (PPS) = 1.5 to 1.8 m implied by the size distribution from the Voyager radio occultation (Table 15.1). The significant differences may be caused, at least in part, by particle clumping due to the gravitational wakes that permeate Ring A. The $Q$-profile in outer Ring A exhibits an interesting systematic decrease of estimated $Q$ with increasing ring radius suggesting systematically decreasing $a_{\max}$ with radius over that region (Fig. 15.7c). The behavior is reminiscent of the systematic X-S differential optical depth behavior in outer Ring A (Fig. 15.1c), although the latter is likely more related to variations in $q$ and/or $a_{\min}$.

### 15.2.10 Caveats Regarding Modeling “Ring Particles” vs. “Self-Gravity Wakes”

In concluding this section, we point out two important limitations of the results summarized in Table 15.1. First, objective comparison of the particle size distribution inferences must be based on the same ring model. Although the classical ring model is at the heart of all three approaches discussed, only the Voyager radio results have been adapted to the perhaps more realistic thin layers ring model. Especially in ring models of likely small vertical extent, it is also desirable to understand electromagnetic interaction with possibly close-packed ring particles.

Second, and perhaps more important, all analysis procedures need to be extended to account for the presence of gravitational wakes in Rings A and B (Chapters 13 and 14). Particle clustering in elongated and preferentially oriented formations fundamentally impacts the observed optical depth.
and its dependence on the ring viewing geometry. It also impacts the strength and shape of the collective near-forward scattering (diffraction) pattern as well as the higher order moments of random fluctuations in the observed signal intensity, all of which being important elements of self-consistent determination of the size distribution. The observations therefore not only provide information about the individual ring particles and their size distribution, but also the physical properties of the wake structure that hosts the individual particles. The challenge therefore is to separate and determine both.

Two idealized models have been used to infer characteristic dimensions of the wake structure in Ring A (Colwell et al. 2006, Hedman et al. 2007). For Cassini radio occultations, preliminary results have been obtained from numerical simulations of signal extinction and forward scattering by ring models that simulate gravitational wakes as clusters of ring particles that are randomly packed in the ring plane (Marouf et al. 2008a,b). The clusters can be of arbitrary width, length, vertical thickness, and packing fraction, and can be embedded in a classical layer of arbitrary thickness. All wake models predict strong dependence of the observed optical depth on wake orientation relative to the observation geometry and ring-opening angle $B$. The dependence invalidates the classical $\tau(\text{oblique}) = \tau(\text{normal})/\sin(|B|)$ scaling, and shows especially strong dependence on the wake orientation when $B$ is small (when the rings are relatively closed). In principle, the measured optical depth variations with observation geometry provide constraints on the physical wake properties (Chapter 13). A corresponding self-consistent inference of the normal optical depth and its variation with wavelength should provide information about the particle size distribution — as was the case in the absence of wakes. From all indications, wakes are so much larger than the radio wavelengths that no wavelength dependence should be expected, only elevation and longitudinal dependence which can be modeled.

Additional complementary information is provided by the near-forward scattered signal measured during radio occultations. Wakes composed of long formations of spatially correlated particles diffract the incident radio signal much like cylindrical structures, with the forward lobe being much stronger and narrower than the diffraction pattern of the constituent particles. The phase coherency required to maintain the cylindrical scattering behavior is limited to very small angles close to the exact forward direction. The randomized phase of wake-diffracted signals scattered to larger angles close to the exact forward direction. The randomized phase of wake-diffracted signals scattered to larger angles cause their intensity to add incoherently, yielding behavior similar to that of the classical model. Numerical simulations validate this behavior (Marouf et al. 2008a,b); comparison of the predicted scattered signal spectra based on the Voyager particle size distribution with those measured by Cassini in inner Ring A reveals the clear presence of a narrower and stronger spectral component — likely due to wakes. Its angular width provides a measure of a characteristic physical dimension of the narrow dimension of the wakes, which is large compared to the individual few-to-tens-of-meter-size particles, clearly distinguishing collective wake effects from individual particle effects. Quantitative results will require careful consideration of the impact of observation geometry and multiple scattering on the diffraction pattern.

In principle, near-forward scattered signal observed during stellar occultations should also be affected by the presence of wakes and the effects on analysis procedures remain to be assessed. Because of the obvious impact on the random ring area blocked during a stellar occultation, the effect of wakes on the excess variance observations is likely to be significant and may be responsible for the differences in typical “sizes” between the Voyager radio and Q-based inferences in Table 15.1. Understanding and quantifying the impact of wakes on all particle size inference techniques will be an active area of current and future research. Hopefully, more general analysis procedures that account for the wakes will not only yield the particle size distribution but also physical properties of the wake structure itself.

### 15.3 “Propeller” Objects: Shards of the Ring

As discussed in Section 15.2, the distribution of “ring particles” follows a powerlaw with a noticeable upper limit on particle radius in the 5–10 m range. Cassini has also discovered an entirely separate class of “particles” in, at least, the A ring, with radii that are up to 100 times larger. These objects are not seen directly, but are revealed by the very characteristic disturbances they create in passing ring material. For lack of a better name they have been dubbed “propeller objects” after the shapes of their associated disturbances (see Chapter 14 for a theoretical discussion relating the objects to their observable disturbances). Here we will summarize the observational aspect of this population and briefly discuss the implications.

The observations were made by Tiscareno et al. (2006, 2009) and Sremcevic et al. (2007). Several hundred objects have been analyzed in terms of their size and radial distribution (Figs. 15.8 and 15.9). Tiscareno et al. (2009) showed that the propeller objects are restricted to three radial bands. These locations are in the mid-A ring, in good agreement with where French et al. (2007) have observed wake-related nonaxisymmetrical brightness variations to maximize as well (Chapter 13). New observations by Cassini (Fig. 15.10) indicate visually the nonuniform distribution of these objects and the potential richness of this database.

It appears that the propeller objects lie on quite a steep size distribution, much steeper than the ring particles themselves,
and that they apparently do not simply connect the largest ring particle with the few known embedded moonlets Pan and Daphnis. Converting number densities of Tiscareno et al. (2006, 2009) into surface mass densities gives $10^{-2}$ g cm$^{-2}$ for the “small” 30 m radius SOI propellers and $10^{-1}$ g cm$^{-2}$ for the “larger” 100 m radius propellers, insignificant relative to typical A ring surface mass densities of 40 g cm$^{-2}$ (Tiscareno et al. 2007; Chapter 13). Because we now have ways of detecting objects in the full size range between ring particles and revealed moonlets, it seems that the mass inventory of the A ring is now complete. As yet, no propeller objects have been discovered in the B ring.

15.4 Ring Particle Composition, Its Radial Variations, and Comparison with Other Icy Objects

In this section we review and preview studies directly related to the composition of the particles of the main rings. We start with a discussion of some of typical observations, the advantages brought to bear by Cassini over prior studies, and some observational challenges. We present ring spectra through the near- and thermal-infrared, visual, and UV spectral regions. We first present large-scale radial averages at low phase angle, reaching some general qualitative conclusions about which materials are, and are not, found in the rings. We then show how the spectra of broad regions (A, B, C, Cassini Division, F ring) vary with phase angle, and discuss the significance. We next select certain key spectral properties and show how they vary with radius on finer scales. These radial spectral variations suggest radial variation of composition, although their significance remains unclear in detail.

Next, we discuss the analysis needed to obtain particle composition from spectral observations, involving models of both the ring layer as a whole, and of the grainy surfaces of the ring particles. Some model studies have attempted to extract both surface grain size and material composition from observed spectra; we discuss these and describe two interesting options for explaining ring color in terms of ring composition. Finally, we compare and contrast the spectral properties of the rings with those of a number of icy objects from the Saturn system and beyond as a prelude to the discussion of ring provenance in Section 15.6.

15.4.1 Observations

The reflected brightness of Saturn’s rings varies with wavelength $\lambda$, solar incidence, phase, and ring opening angles, and radial location due to the scattering properties of individual ring particles (Section 15.4.6.2) as well as their collective spatial and size distributions (Sections 15.2, 15.4.6.1, and below). Denoting the incident solar flux across some spectral band as $\pi F$ erg cm$^{-2}$ s$^{-1}$, the observed intensity $I$ of the rings (erg cm$^{-2}$ s$^{-1}$ str$^{-1}$) in some geometry is ratioed to the intensity of a perfect Lambert surface (incident flux/$\pi F$), defining the normalized reflectance $I/F$. In the case of the rings, this $I/F$ includes the effects of finite ring optical depth.

1 The ring opening angle $B$ is the elevation angle of the observer from the ring plane. The phase angle $\alpha$ is the angle between the sun, the viewed target, and the observer, or the angle between the sun and observer as seen from the target. The phase angle is zero in direct backscattering.
the effects of multiple scattering between particles, and the properties of individual particles which can be regarded as small (but very irregular) moons. Moreover, rings generally contain some admixture of wavelength-size “dust” particles which scatter light in a much different way than macroscopic objects, so the variation of ring $I/F$ with phase angle can become quite complicated; the reader is referred to Cuzzi et al. (1984, 2002) or Cuzzi (1985) for more detail on photometric definitions.

Observations of Saturn’s rings from Earth are restricted to solar phase angles $\alpha < 6^\circ$ and ring opening angles $B < 26^\circ$, but in spite of these limitations a great deal of interesting variation with viewing geometry has been seen. The Voyager 1 and 2 flybys in 1980 and 1981 provided snapshots of the rings at two illumination geometries over a wide range of phase angles. Cassini observations are a quantum step forward in covering a full range of viewer geometry and solar incidence angle, and in providing numerous stellar and radio occultations of the rings to determine their optical depth at a variety of elevation angles and longitudes. Cassini also provided our first true spectroscopy at UV, near-IR, and thermal-IR wavelengths.

In most cases we do not observe particles acting alone, but as a thick slab where particles can cover and illuminate each other. Relating the overall ring reflectance to the individual particle reflectance is a complex matter (Section 15.4.6.1). Once the albedo and phase function of a typical particle are known from models of the ring layer, one then turns to a different kind of model to infer the particle’s composition by modeling multiple scattering of photons in its granular regolith, complicated by facet-related shadowing effects. Several models have emerged to handle this problem. All of them are simplified and their various assumptions introduce uncertainty in the properties inferred – primarily, regolith grain size and composition. These models are discussed in Section 15.4.6.2. Also, numerous Cassini occultation studies have shown that, on a local scale of hundreds of meters, most of the rings resolve into inhomogeneous collections of dense “self-gravity wakes” which are azimuthally extended, tilted to the orbital direction, and perhaps entirely opaque, separated by much more transparent gaps (see Chapters 13 and 14). This structure greatly complicates the modeling of observed ring brightness as a function of viewing geometry.

Another complication in studies of ring particle properties is that the rings are not only illuminated by the sun, but also by reflected light from Saturn, which is not spectrally neutral, and the relative importance of this illumination varies with viewing geometry. The top panel in Fig. 15.11 is a VIMS reflected light image at a wavelength where scattered light from Saturn is very low due to strong methane absorption in Saturn’s atmosphere. The bottom two panels represent ring brightness at a wavelength where Saturn’s methane is known to absorb, but weakly, thus allowing us to detect where “Saturnshine” is reflected from Saturn to the rings and then back to the spacecraft. The most obvious effect is the angular brightening near the 10-o’clock position due to backscattering of light from Saturn’s fully lit hemisphere by the rings. At this phase angle (135 degrees), the Saturn
tering (Section 15.4.6.1), so are most easily interpreted as
of multiple interparticle scattering of dust grain forward scat-
complications of Saturnshine and most of the complications
and near (but not too near) the shadow boundary avoid all the
VIMS spectra of the lit face of the rings at low phase angles,
15.4.2 Global VIMS Ring Spectra and Overall
methane absorptions are also known to lie.
weak non-ice spectral signatures where strong atmospheric
et al. 2007) – negligible except when searching for extremely
Earth-based observations), models suggest that Saturnshine
There is some evidence for contamination of C ring spec-
tra taken during Saturn Orbit Insertion (SOI), where the C
ring pointing was extremely close to the edge of the planet’s
shadow (Nicholson et al. 2008). Other (primarily radial) vari-
ations in the lower two panels of Fig. 15.11 may not repre-
sent Saturnshine, but instead actual ring spectral variations
between, specifically, the Cassini Division and C ring, and
the A and B rings. At low phase angles (characterizing all
Earth-based observations), models suggest that Saturnshine
should be in the percent range (Dones et al. 1993; French
et al. 2007) – negligible except when searching for extremely
weak non-ice spectral signatures where strong atmospheric
methane absorptions are also known to lie.
noon position on the B ring reflects so much Saturnshine
that the methane band depths in ring spectra are on the
order of 50% (the C ring is even more strongly affected). A
less obvious but even stronger effect is the bright line tracing
the shadow edge on the rings, due to Saturn’s penumbra or
light refracted through its high atmosphere onto the rings.
There is some evidence for contamination of C ring spec-
tra during Saturn Orbit Insertion (SOI), where the C
ring pointing was extremely close to the edge of the planet’s
shadow (Nicholson et al. 2008). Other (primarily radial) vari-
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weak non-ice spectral signatures where strong atmospheric
methane absorptions are also known to lie.

15.4.2 Global VIMS Ring Spectra and Overall
Composition

VIMS spectra of the lit face of the rings at low phase angles,
and near (but not too near) the shadow boundary avoid all the
complications of Saturnshine and most of the complications
of multiple interparticle scattering of dust grain forward scat-
tering (Section 15.4.6.1), so are most easily interpreted as

15.4.3 Regional and Phase Angle Variations
of VIMS Ring Spectra

Below we break the VIMS spectra, from Clark et al. 2008a,
down further, showing how the I/F of each main region
varies with phase angle (Figs. 15.16–15.20). Spectra at high
phase angles are complicated by multiple scattering between
Fig. 15.12 Average reflectance spectra of different regions of the main rings (A, B, CD) as measured by VIMS. The ring distances for each spectrum are: F-ring: 140,200 km, A-outer: 134,000–136,700, A-inner: 123,700–125,700, Cassini Division: 118,000–125,700, B-outer: 103,000–117,000, C-ring: 75,000–87,000 km. Data from Cassini VIMS Rev 75, LATPHASE observation at 19 degrees phase angle. The spectra are fill-factor corrected (from Clark et al. 2008b).

Fig. 15.13 Changing abundance of CO$_2$ in the icy satellites and rings. No CO$_2$ is seen in the rings. From Clark et al. (2008b).

ring particles (which deepens spectral features) and also by primarily diffractive forward scattering by dust grains (which is spectrally featureless). The main rings show decreasing $I/F$ with increasing phase angle, and strong ice spectral features, up to at least 135 degrees phase angle (Figs. 15.16–15.19), as expected for large particles with grainy surfaces. The F-ring $I/F$ increases with phase angle from 19 to 178.5 degrees, indicating forward scattering by a predominance of small particles (Showalter et al. 1992). But the F-ring also shows the 1.5 and 2 $\mu$m ice bands and 3.1 $\mu$m Fresnel peak (Fig. 15.20), consistent with large grains of crystalline ice, showing that it also contains particles at least several millimeters in diameter (Clark et al. 2008a,b), consistent with the fact that the F ring core, at least, displays a significant (if variable) radio occultation signal (Section 15.2).

The weakening of the main 1.5-, 2-, and 3 $\mu$m ice spectral features in the 178.5 degree phase spectra of all the rings...

Fig. 15.14 B-ring spectrum (black) is compared to amorphous (red) and crystalline (blue) water ice spectral models using optical constants from Mastrapa et al. (2008, 2009). The absorption band positions and shapes indicate the B-ring spectra are dominated by crystalline water ice. The B-ring spectrum is for the 103,000 to 117,000 km region. From Clark et al. (2008b).
Fig. 15.15 The 3.1 μm Fresnel reflectance peak in Saturn’s A-ring (red), B-ring (blue), Cassini Division (grey), and C ring (gold). VIMS spectra are compared to that of crystalline water ice (black). The observed peak width and position, along with the side features at 3.2 and 2.94 μm, also indicate crystalline H₂O ice. The ring distances for each spectrum are: A-outer: 134,000–136,700 km, A-middle: 126,000–134,000, A-inner: 123,700–125,700, Cassini Division: 118,000–125,700, B-outer: 103,000–117,000, B-inner: 92,000–103,000, C-ring: 75,000–87,000 km. The feature at 2.94 μm occurs at an order-sorting filter gap in the VIMS spectrometer, so has greater uncertainty. From Clark et al. (2008b)

Fig. 15.16 Cassini VIMS spectra of the middle A ring (126,000–134,000 km) as a function of phase angle. The <3 degrees phase is from Rev 44, 0PHASE001, 19 degrees from Rev 75, LATPHASE001, 135 degrees from Rev A, LATPHASE001, 178.5 degrees from Rev 28, HIPHASE001, From Clark et al. (2008b)

Fig. 15.17 Cassini VIMS spectra of the outer B ring (103,000–117,000 km) as a function of phase angle (observation sets are the same as in Fig. 15.16). From Clark et al. (2008b)

Fig. 15.18 Cassini VIMS spectra of the C ring (75,000–87,000 km) as a function of phase angle (observation sets are the same as in Fig. 15.16). From Clark et al. (2008b)

The broad hump in spectral shape in the C and F-rings at very high phase angles, being dominated by diffraction, constrains the grain size distribution, and detailed modeling is in progress (Hedman et al. 2008, Vahidinia et al. 2008). The UV absorber and some weak 1.5- and 2.0 μm features are visible in all the main ring spectra to the highest observed phase angle. The simplest interpretation of this is that there is some fraction of multiply scattered light (in the particle regoliths or possibly between large ring particles) reaching the observer, perhaps mixed with a not-entirely-dominant, spectrally featureless contribution from tiny, forward-scattering grains.

In the highest phase angle spectra, two dips appear near 3 μm: the first is probably the Christiansen frequency of...
water ice (Nicholson et al. 2007, Vahidinia et al. 2008, Clark et al. 2008b); the second is at the location of an order sorting filter gap in the VIMS instrument, as well as the N-H stretch fundamental, so needs confirmation by a different instrument or observing geometry.

15.4.4 UVIS Spectra of the Main Ring Regions

UVIS $I/F$ spectra are shown in Fig. 15.21 at four 4,000-km-wide locations in the main rings (Bradley et al. 2009). The bin centers are at 87,400 km (C ring), 111,400 km (B ring), 119,400 km (Cassini Division), and 127,400 km (A ring) from Saturn center, respectively. The sharp decrease in $I/F$ below 175 nm is due to water ice absorption of incident solar photons. Also apparent above 175 nm is the variation in $I/F$ for the different regions of the rings. The difference between the ring brightnesses are due at least partly to their different optical depths.

15.4.5 Radial Profiles of ISS and VIMS Spectral Properties

ISS, VIMS, and CIRS observations can be used to explore the radial variation of ring composition in a qualitative fashion, until detailed modeling allows ring particle albedos (and their spectral variation) to be extracted from ring brightness (see Sections 15.4.1 and 15.4.6.1).

15.4.5.1 Radial Profiles of ISS and VIMS Spectral Properties

Estrada and Cuzzi (1996) and Estrada et al. (2003) generated color ratios as a function of radius from Voyager color images. Spectral slopes are equivalent to color ratios in bright regions, and are less sensitive to uncertain backgrounds in regions of low $I/F$. We create normalized spectral slopes $S_{ij}$ between wavelengths $\lambda_i$ and $\lambda_j$, for the full ring system from lit face data, using both VIMS and ISS data. For VIMS data we present slopes between 350–520 nm ($S_{350-520}$) and 520–950 nm ($S_{520-950}$) (Filacchione et al. 2007, 2008a,b; Nicholson et al. 2008). The 520–950 nm slopes are new to Cassini, and were not observed by Voyager. Cuzzi et al. (2002) attempted some analysis of HST profiles at long
Color images in multiple filters were obtained on 2004-day 347 as part of the best fitting linear trend to the scattered light problems. The VIMS spectral slopes are defined as $S_{ij} = \frac{I/F_j - I/F_i}{(I/F_j)\Delta\lambda_{ij}}$ (15.15)

Normalization by the $I/F$ itself removes illumination effects and decouples the ring color from its brightness. For the ISS data we simply construct slopes between the various filter bands UV3 (0.34 $\mu$m), BL1 (0.44 $\mu$m), and GRN (0.55 $\mu$m). Similarly (for the VIMS data) we can define a Band Depth metric $BD_i$, for a band at wavelength $\lambda_i$, typically the 1.5 and 2.0 $\mu$m water bands, as

$$BD_i = \frac{I/F_{cont} - I/F_i}{I/F_{cont}}$$

(15.16)

where $I/F_{cont}$ is the average continuum $I/F$ on both sides of each band (1.345 & 1.790 $\mu$m, and 1.790 & 2.234 $\mu$m respectively).

The data of Fig. 15.22 cover the lit face of the rings. As found by Estrada and Cuzzi (1996), Estrada et al. (2003), and Cuzzi et al. (2002), the slopes (or color ratios) do not merely echo the radial ring brightness variations, but show uncorrelated variations of their own. The C ring and Cassini Division particles are “less red” or more neutral in color than the A and B ring particles, and the colors vary smoothly with radius across very abrupt ring boundaries. The two Cassini ISS profiles split the Voyager spectral range into two spectral ranges, and the radial behavior is different between them at several locations (note 83,000–91,000km, 105,000–110,000, and 120,000–125,000km) – probably indicating radial variation of composition. Notice how the optically thick central B ring is the reddest region in $S_{340-550}$, but the inner B ring is reddest in $S_{340-440}$ (has the deepest UV absorption).

Figure 15.23 shows comparable results from a VIMS radial scan taken at Saturn Orbit Insertion (SOI; Nicholson et al. 2008). The $S_{350-550}$ color ratios (blue curve) are in good qualitative agreement with those of Estrada et al. (2003) and those in Fig. 15.22, even though the VIMS observations were of the unlit face and the other observations were of the lit face. In particular, smooth radial variations are seen across abrupt boundaries between regions of different optical depth, such as the A ring inner edge denoted CD-A. The inner part of the Cassini division (118,000–120,500km) is less red than the A ring at short visual wavelengths ($S_{350-550}$) but more red at long visual wavelengths ($S_{550-950}$). Figure 15.23 also shows that $S_{350-550}$ correlates quite well with the water ice band depths $BD_{1.5}$ and $BD_{2.0}$. This suggests that the UV absorber is localized to, and perhaps even residing within, the water ice regolith grains. The distinctly different behavior of $S_{350-950}$ indicates that some different material has a greater abundance in the Cassini Division.

Following Nicholson et al. (2008), we created new full-ring visual slope and BD plots from VIMS lit face data at somewhat lower resolution (Fig. 15.24). The VIMS visual slope profiles of Fig. 15.24 repeat the overall behavior of the ISS profiles in Fig. 15.22, but at lower resolution and with more scatter due to lower fidelity geometrical registration; they are adequate for our purposes of exploring general regional behavior (Section 15.4.9). The two water ice BD radial profiles are correlated, showing the same radial variations; the BD are largest in the A (130,000km to Encke gap) and B rings (from 104,000 to 116,000km). In the outer B ring (from 104,000 to 117,000km) the BD are almost flat, with a local minimum at 109,000km; in the central B ring (from 98,500 to 104,000km) there are several regions with high BD, coinciding with the visual wavelength “red bands” of Estrada and Cuzzi (1996); in the inner B ring (92,000 to 98,500km) the BD are flat to moderately decreasing towards the inner part; Nicholson et al. (2008), in their higher

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2 Color images in multiple filters were obtained on 2004-day 347 as part of an ISS observation RADCOLOR001.PRIME, at phase angle = 45.2°, elevation angle = 4.1°, and distance from Saturn of approximately 120000km (7.2km/pixel). The data were calibrated using standard techniques and scanned radially with approximately 100 pixel azimuthal averaging. See Porco et al. (2005) for a description of the filter wavelengths and widths.

3 The data come from rings mosaic S36-SUBML001, acquired by VIMS on a CIRS-prime observation, on 19–20 December 2007 with a solar phase angle of 32°, a solar elevation angle of –12°, and from a mean distance of about 545000 km, giving a radial resolution of 125 km.
15 Ring Particle Composition and Size Distribution

Fig. 15.23 Top: Radial profiles of ring I/F at wavelengths where water ice does not (blue) and does (red) absorb light, from SOI VIMS data; (bottom) comparison of two different visual wavelength spectral slopes (S_{350–520} and S_{520–950}) and two different water ice band depths (BD_{1.5} and BD_{2.0}). S_{350–520}, indicating the short-wavelength redness of the rings or the abundance of the UV absorber, tracks the water ice band depths very closely, while S_{520–950}, indicating the longer-wavelength ring color, does not (Nicholson et al. 2008).

resolution data, find some evidence of structure in the inner B ring. The middle and inner C ring is similar to the inner CD and the outer part of the C ring (outside the Maxwell gap) is similar to the outer part of the CD. As seen in greater detail in the A ring and Cassini Division by Nicholson et al. (2008; Fig. 15.23), S_{350–520} correlates extremely well everywhere with BD_{1.5} and BD_{2.0}, indicating a close spatial correlation between the UV absorber and the water ice, but S_{520–950} is decorrelated from BD_{1.5}, BD_{2.0}, and S_{350–520}, hinting at a different constituent.

15.4.5.2 Particle Albedo Variation from CIRS Ring Temperature Profiles

It is possible to estimate the albedo of a ring particle from its physical temperature; lower albedo particles absorb more sunlight and are warmer. Cassini CIRS observations over the 10–100 μm spectral range can be fit spectrally to determine the physical temperature of the ring particles, assuming the particle emissivity is independent of wavelength (see Section 15.4.7.2 for how emissivity variation is a major concern at longer wavelengths, however). In Fig. 15.25 we compare a radial profile of ring temperature obtained by CIRS⁴ with a VIMS BD profile (Fig. 15.24).

The C ring and Cassini Division particles are considerably warmer than the A and B ring particles, as was first observed by Voyager when the Sun was at a much lower elevation angle (Hanel et al. 1982; see Esposito et al. 1984 for a review of ring thermal models). This is a direct indication of lower albedos, consistent with the idea that the two lower optical depth regions are more polluted by non-icy material. Low albedos of the C ring and Cassini division particles (0.15, relative to 0.5 for the A and B ring particles) were reported by Smith et al. (1981). A more polluted particle composition can explain the smaller VIMS water ice band depths seen

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⁴ CIRS lit face scan, on the West Ansa, obtained in 2006 (day 349) near zero phase angle (~5.9 deg) when the Sun was ~14.6 deg south of the ring plane. The radial distance between each CIRS footprint was ~100 km on the ring plane, although the radial resolution was limited by the field of view to ~1700–1800 km. For clarity, the data have been binned every 200 km.
Fig. 15.24 Top panel: Radial profiles of the visible spectral slopes $S_{350-520}$ (blue line, magnification factor $\times 300$) and $S_{520-950}$ (red line, $\times 1,000$); for comparison an $I/F$ profile measured at 550 nm is shown (black line, $\times 4$). Bottom panel: water ice band depths at 1.5 $\mu$m (blue line) and 2.0 $\mu$m (red line); an $I/F$ profile at 1.822 $\mu$m is shown (black line, $\times 3$). These 125 km per sample profiles are retrieved by VIMS from S36-SUBML001 mosaic ($32^\circ$ solar phase angle).

Fig. 15.25 Radial profiles of CIRS ring temperature at low phase angle (black line) and VIMS water ice band depth (red and blue lines). Also shown is a plot of optical depth from UVIS (J. Colwell, personal communication 2007). The ring particle temperature is higher in the C ring and Cassini Division; it also decreases outwards in the A ring and has local minima in dense, optically thick regions of the inner B ring; note that in the 101,000–104,000 km and 108,000–109,000 km regions the temperature correlation with ice band depth reverses sign from the global behavior described above.
in these regions (see Section 15.4.7). However, this comparison raises some puzzles. The simple interpretation above is not consistent with the behavior in the 101,000–104,000 and 108,000–109,000 km regions, or in the very outermost parts of the A ring, where both ice band depth and particle temperature decrease in unison. Perhaps here regolith grain size itself is playing a role (Section 15.4.7.2), or perhaps, for the outer A ring, impinging E ring material or plasma play a role (Farrell et al. 2008, Jurac and Richardson 2007).

15.4.6 Modeling Individual Particle Properties from Observed Ring Reflectance

As discussed in the introduction to this section, several distinct stages of modeling are required to extract ring composition and particle properties from ring I/F observations. Here we discuss two in turn.

15.4.6.1 Modeling the Layer of Ring Particles as a Whole

In most cases we do not observe particles acting alone, but as a thick slab where particles can cover and illuminate each other. Relating the overall ring reflectance to the individual particle reflectance is a complex matter. Voyager-era radiative transfer models generally relied on classical concepts of ring structure (low volume density and a vertical structure many well-separated particles in extent). Layers of this kind can be modeled by traditional doubling-adding techniques (e.g., Dones et al. 1993; Doyle et al. 1989). The ring regions and viewing geometries where the classical models are the most successful are those where single scattering is dominant (low phase angle, low albedo particles and/or where the optical depth is low; e.g., Cuzzi et al. 1984, Cooke 1991, Cuzzi et al. 2002, Nicholson et al. 2008). However, even in the Voyager era there were observational indications that these models were unsatisfactory in the A and B rings, suggesting a dense, and indeed dynamically preferred, ring vertical structure (Dones et al. 1989, 1993).

Recent HST (Cuzzi et al. 2002, French et al. 2007) and Cassini observations (Hapke et al. 2005, 2006, Nelson et al. 2006) and their analyses (see Appendix), have called into question the classical, many-particle-thick ring that can be modeled using doubling techniques or their single-scattering limits for densely packed regions of moderate to high optical depth (Cuzzi et al. 2002, Salo and Karjalainen 2003, Porco et al. 2008, Chambers and Cuzzi 2008). Recent ring radiative transfer models using ray-tracing techniques to address layers of closely-packed particles (Salo and Karjalainen 2003, Porco et al. 2008, Chambers and Cuzzi 2008) are removing the limitations of traditional models, and can even handle the anisotropy of self-gravity wakes, but still make a number of simplifying assumptions (spherical particles with idealized surface scattering laws, for instance). Clearly, one cannot extract actual particle albedos from observed ring brightnesses until this modeling problem has been addressed carefully. However, for studying spectral variations of reflectivity rather than absolute value, and at low phase angle observations of the lit face, assuming single scattering by individual surfaces and comparing to laboratory reflectance spectra might be acceptable (see Sections 15.4.2–15.4.5).

A concern in interpreting ring spectra in terms of grain size and/or compositional makeup, is how much light comes from multiple scattering in the ring particle regoliths versus how much comes from multiple scattering between ring particles, or interparticle scattering. The amount of multiple interparticle scattering should increase with phase angle, which will increase the spectral contrast and affect compositional inferences. Cuzzi et al. (2002) found from HST data that the rings redden significantly with increasing phase angle, over the spectral range where the rings are already red. At the same time, they found no tendency for the ring color to vary with ring opening angle at a given phase angle, or where the spectrum of the rings is flat. They concluded that multiple scattering within the near-surface of individual ring particles was important, but that multiple scattering between separate ring particles in a vertically extended layer was not.

An even more sensitive measure of spectral contrast is the I/F ratio between 2.86 and 2.6 μm; 2.86 μm is in the deepest part of the water ice absorption band, and 2.6 μm is a nearby wavelength where absorption by ice is fairly weak; multiple scatterings quickly amplify this brightness difference. Examining the spectral contrast in the Cassini VIMS data, Clark et al. (2008a) found that the 2.86/2.6 μm brightness ratio in the rings stayed relatively constant at low phase angles, decreasing slightly at 135° phase and thus indicating a small increase in multiple scattering between low and moderate phase angles. The phase variation of the 2.86–2.6 μm ratio is always weaker for the rings than seen in pure ice, consistent with scattering from an icy regolith with trace contaminants but inconsistent with substantial interparticle scattering (Clark et al. 2008b).

These results suggest that there is little interparticle scattering in the rings at low phase angles (at least), which allows us to directly compare low phase spectra of the rings with laboratory analog spectral data and standard regolith radiative transfer models for single surfaces (next section).

15.4.6.2 Modeling Ring Particle Regoliths

This step consists of modeling the reflectance of a surface element of a single ring particle in terms of the combined
multiple scatterings of all the grains in its regolith. This general class of models is often generally referred to as “Hapke theory” after its most popular variant (Hapke 1981, 1993), and is more generically called a Regolith Radiative Transfer (RRT) model. The models start by deriving an individual grain albedo, assuming geometric optics where a particle is so much larger than a wavelength that Fresnel reflection coefficients can be averaged over; thus the theory is not applicable to regolith grains of wavelength size or smaller. RRT models then proceed by calculating the multiple scattering between grains, in different ways. Reflectance spectra can then be computed for pure minerals or mineral mixtures with any grain size distribution, using the known refractive indices of the various materials. Clark and Roush (1984) also showed that a reflectance spectrum can be inverted to determine quantitative information on the abundances and grain sizes of each component. The inversion of reflectance to quantitative abundance has been tested in laboratory mixtures (e.g., Johnson et al. 1988, 1992; Clark 1983, Mustard and Pieters 1987a, 1989; Shipman and Adams 1987; Sunshine and Pieters 1990, 1991; Sunshine et al. 1990; Gaffey et al. 1993, Mustard and Pieters 1987b, Li et al. 1996, Adams et al. 1993 and references therein). Generally the results are fairly good when the regolith grains are all very large compared to a wavelength.

Perhaps the oldest RRT is generically referred to as “Mie-Conel” theory (Conel 1969). Instead of assuming geometrical optics to get the grain albedo, it uses Mie theory to determine the albedo and degree of forward scattering for an isolated particle, and a transformation suggested by the two-stream approximation of radiative transfer to handle the multiple scattering component. The approach used by Hansen and McCord (2004) and Filacchione et al. (2008a,b) is similar, replacing the two-stream treatment of multiple scattering with a doubling model. Moersch and Christensen (1995) tested a generic Mie-Conel theory and Hapke theory against actual laboratory reflectance spectra where the composition (SiO$_2$) and particle size (tens of microns) were known; general agreement was fair, but detailed agreement in and out of absorption features was not good for any of the theories—possibly because here, the grain size was not always much larger than the wavelength. A more recent RRT has been developed by Shkuratov et al. (1999). The albedo of an individual grain is found in a way similar to Hapke theory, but the degree of forward scattering by such a grain is retained. This model does not predict particle phase functions. Poulet et al. (2003) compared results obtained using Shkuratov and Hapke theory, and found that Hapke theory underestimates spectral contrasts relative to Shkuratov theory for the same regolith grain size because of this difference. The size of the effect increases with brighter surfaces. Because of these systematic uncertainties, caution must be exercised regarding quantitative compositional inferences from models such as these.

Moreover, the actual phase function of the ring particle as a whole (which enters into layer models) must account for the role of shadowing by rough surfaces and facets. Poulet et al. (2003) derived a roughness parameter from HST observations over a small range of low phase angles, and found it to be extremely large relative to the value found to characterize icy satellites in general. This suggests that the ring particle surfaces might be extremely lumpy—not inconsistent with our mental picture of ring ‘particles’ as aggregates. Dones et al. (1993) showed that the wavelength-dependent single-particle phase function $P_\alpha(\alpha)$ was well-matched by a rather strongly backscattering power law: $P_\alpha(\alpha) = c_n(\pi-\alpha)^n$ where $c_n$ is a normalization constant and $n = 3.3$ gives a good match to the phase function of Callisto and to Saturn’s A ring particles. Hapke (1984; 1993, his Chapter 12) and Kreslavsky and Shkuratov (2003, and references therein) present theories including macroscopic shadowing, which result in phase functions having this shape. This strongly backscattering behavior leads to the general dominance of single scattering by the rings at low phase angle (Cuzzi et al. 1984, 2002; Dones et al. 1993).

15.4.7 Laboratory and Model Water Abundance and Regolith Grain Size

We first deal with the more straightforward observational geometries (ring spectra at low phase angles) and describe compositional and grain size implications we can obtain from these observations. In the Appendix, we present a discussion of modeling the zero-phase opposition effect, which combines the complications of regolith and ring layer properties.

15.4.7.1 Water Ice Band Depths from VIMS Data

Laboratory ice spectra at various grain sizes are shown in Fig. 15.26. The spectral contrasts from 2.6 to 2.86 µm for spectra of fine to medium sized grains provide the best match to A and B ring data (Figs. 15.16–19).

Below we interpret band depth variations in terms of grain size, but an important caveat should be kept in mind. The overall light backscattered by a regolith-covered particle is (nonlinearly) related to the energy absorbed by a single regolith grain. For grains which are large compared to a wavelength (the regime of all current RRT models), the energy absorbed by a grain is determined by the product of the
absorption coefficient and a typical path length, say the grain diameter (e.g., Irvine and Pollack 1968, Hapke 1981). Because we know the relative amount of water ice varies with location, we must realize that radial variations in band depth can map out either grain size variation, compositional variation, or a combination. The C ring and Cassini Division particles are more “polluted” with nonicy material, based on their lower albedoes (sect. 15.4.5.2); thus their weaker ice band depths might not represent smaller grains, but less water-rich grain composition.

Clark et al. (2008b) compared the ice band depths in Saturn’s rings spectra to that from Hapke models of ice spectra (Fig. 15.27). They found the mean grain size of ice to be on the order of 30–50 μm diameter in the A and B-rings.

Another way to map the regolith grain size is through the $I/F(3.6\,\mu m)/I/F(1.822\,\mu m)$ ratio. Both lab data and models for pure water ice (Clark and Lucey 1984, Hansen and McCord 2004, Jaumann et al. 2008) indicate that the reflectance at 3.6 μm depends on the water ice grain size (higher reflectances are measured for fine grains). The 3.6 μm reflectance is normalized to that at 1.822 μm to remove the effects of radially variable optical depth. Figure 15.28 (Filacchione et al. 2008b) uses a Hansen-McCord (2004) RRT model and infers particle sizes about twice as large, across the rings, as obtained from the analysis of Fig. 15.27. The size difference could be due to the different band used, or to the different regolith radiative transfer model used, illustrating the caveats expressed in Section 15.4.6.2 above. Nevertheless, the radial variation is of interest as a possible indication of compositional variations.

### 15.4.7.2 Regolith Properties from CIRS Spectra at Long Thermal Infrared Wavelengths

The far infrared spectra of the main rings exhibit a decrease in spectral intensity, or brightness temperature, relative to a black body at wavelengths longer than 100 μm (Fig. 15.29a).
This rolloff in intensity continues to microwave wavelengths where the ring brightness temperatures are only a few degrees K, providing our currently strongest evidence that the rings are nearly pure water ice even below their surfaces (Chapter 2; see Esposito et al. 1984 for a discussion). Spilker et al. (2005) corrected for ring optical depth effects by fitting the shape of the ring intensity spectrum between 100–400 cm\(^{-1}\), where the particle emissivities and ring optical depths are likely to be wavelength-independent. In this way a temperature close to the physical temperature is obtained at the shortest wavelengths, and the rolloff towards long wavelengths can be ascribed to decreasing emissivity of surface grains. The CIRS short-wavelength ring temperatures are lower than groundbased values because they are made at higher phase angles (120° for the A and C rings, 67° for the B ring), where more shadowed area is visible (Spilker et al. 2006, Altobelli et al. 2008).

A simple model was constructed by calculating the spectral albedos of different particle sizes, assuming Mie theory and water ice composition (Fig. 15.29b). High-albedo particles have the low emissivities needed to cause the ring brightness temperature to roll off as seen in Fig. 15.29a. For particles larger than a cm or so, no spectral albedo variation is seen; thus most emitting particles must be smaller in size and are most plausibly ascribed to regolith grains on actual ring particles (Section 15.2). Moreover, strong spectral variation of water ice itself at 20–70 \(\mu\)m wavelengths (Warren 1984; Johnson and Atreya 1996; solid lines in Fig. 15.29b) is not observed, arguing for a broad distribution of regolith grain sizes (dashed line in Fig. 15.29b). Specifically, a powerlaw of the form \(r^{-q}\) (\(q = 3.4\)) provided the average grain albedo as a function of wavelength. Note that other studies have found it advantageous to model a broad regolith grain size distribution (Section 15.4.8). The doubling code used to calculate emergent intensity assumes independent, well-separated particles, not in fact valid in a regolith for these combinations of wavelength and particle size (Section 15.4.6.2). New theories will have to be employed which properly account for close packing of particles which are wavelength-sized, nonspherical and clumpy. However, these results are certainly indicative that the properties of realistic ring particle regoliths can account in a general way for the observed brightness temperature rolloff in the far-infrared.

### 15.4.8 Global Models of Ring Composition

Poulet et al. (2003) conducted the most recent comprehensive study of the ring composition prior to Cassini arrival (see Poulet et al. (2003) or Chapter 2, for a summary of previous studies of the composition of Saturn’s rings). They modeled their ring spectra (Fig. 15.30) with a radiative transfer model by Shkuratov et al. (1999), using ice, a dark colorless component (amorphous carbon) to adjust the albedo, and a UV absorber (organic tholins) to reproduce the UV-visible reddening. Their study concluded that spectra of the A and B rings indicated water ice with no evidence for other volatile ices. The depths of the ice absorptions differed for each ring, and their model called for a wide spread in grain sizes from 10 to 1,000 \(\mu\)m to explain all the band strengths. They concluded that the lower albedo and the less blue slope in the near-infrared reflectance of the C ring indicated a different fractional amount of dark material relative to the A and B
15 Ring Particle Composition and Size Distribution

Fig. 15.30 Ground-based visual and near-IR spectra of Saturn’s B ring (Poulet et al. 2003) and their best-fit model, which employed three different grain sizes to mimic a grain size distribution, and a combination of ice, carbon, and tholins. See text for discussion. Apparent dip at $\lambda > 3.3\ \mu m$ might be an (unobserved) model signature of tholins, or might be an artifact of how refractive indices were handled in the region $\lambda > 2.9\ \mu m^5$

rings, as did Cuzzi and Estrada (1998) and Smith et al. (1981) from Voyager data alone. Moreover, they required a different kind of contaminant mixing in the C ring compared to the A and B rings. Poulet et al. (2003) interpreted their C-ring spectra as evidence for C-H absorption in the rings (most easily seen in their ratio spectra). However, C-ring spectra from Cassini VIMS data, obtained near the shadow boundary (but away from the refracted light problem zone of Fig. 15.11), show no such absorptions. The C-H features seen by Poulet et al. (2003) might have been due to light scattered from Saturn directly into the detector.

Their model spectra provided good matches to the UV/Visible spectra of the rings and the ice absorptions in the 1–2.5 $\mu m$ region, but close inspection of their models shows distortion in the 3.3 $\mu m$ region which probably represents inappropriate water ice optical constants. Figure 15.31 compares the spectral variation of the imaginary indices of water ice and several tholins. Notice that one of these materials has a spectral feature near 3.4 $\mu m$ which might be visible in an ice mixture if it had abundance comparable to the ice; two other candidates would not be spectrally obvious even in significant proportions. However, in the models of Poulet et al. (2003), less than a percent of Tholins were needed to provide the red color of the rings (the grain refractive index is a volume-weighted average of the indices of the materials present). Thus it seems that none of these tholins would be obvious in the ring spectra at 3.4 $\mu m$, if they were present in the proposed abundances.

“Tholins” are only one kind of organic material – created as huge macromolecules by UV irradiation and/or charged particle bombardment of various simple organics like CH$_4$, N$_2$, NH$_3$, and H$_2$O (Cruikshank et al. 2005 and references therein). Another possible alternate coloring agent is one of the many classes of “PAHs” (Polycyclic Aromatic Hydrocarbons), which are much simpler molecules typically consisting of large patches of perhaps only a few to dozens of benzene rings (see Section 15.6.3 for more detail). As shown in Fig. 15.32, many PAHs are visually reddish and indeed might be the fundamental source of the reddening caused by Tholins, which are enormous arrangements of many PAHs in different orientations.

Comparisons between the spectra of rings and reddish outer solar system objects which are generally presumed to be the carriers of the Tholins (Cruikshank et al. 2005, Barucci et al. 2008) also show some qualitative differences in shape (Section 15.5). Thus, one might wish to explore other options for explaining the ring redness. One such option was suggested to us by the newly-discovered oxygen (O, O$_2$) rich ring atmosphere (Section 15.5). If there ever were a component of the rings made of fine grained iron, such as is found in meteorites, one can speculate that this iron could be “rusted” over time in this atmosphere into the oxidized iron oxide hematite, which has attractive spectral properties in the ring context.

Fig. 15.31 Comparison of the imaginary refractive index $n_i$ of water ice with that of three tholins (data from Cruikshank et al. 2005); the wavelength variation of $n_i$ is primarily responsible for observed absorption features. Only one tholin has a noticeable spectral feature near 3.4 microns, and the relative importance of this feature would be negligible in the sub-percent mixing ratios needed to explain the reddish ring color (notice how $n_i$ for tholins dominates at visual wavelengths, even if the tholins were present in very small abundances.

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5 Suspecting a temperature-dependent effect, Poulet et al. (2003) shifted the optical constants of ice by 0.07$\mu m$ for wavelengths longer than 2.9$\mu m$ – right where a glitch is seen in the models (F. Poulet, personal communication, 2008). More modeling work needs to be done using the most up to date optical constants of water ice at the appropriate temperature.
Fig. 15.32 Samples of six different Polycyclic Aromatic Hydrocarbon ("PAH") molecules; from left to right and back to front: C_{48}H_{20}; C_{22}H_{12}; C_{20}H_{12}; C_{22}H_{12}; and C_{36}H_{16}, C_{40}H_{18}, C_{42}H_{48}. PAHs dominate the organic component of the interstellar medium. The visual colors are all reddish. These are much smaller molecules than the macromolecular "tholins" that are often used to mimic planetary organics; they may act alone or as subunits within tholins to provide a reddening agent (see also Section 15.6.3)

Nanohematite (very fine-grained hematite or Fe_{2}O_{3}) is a strong UV absorber that matches the spectral structure observed in spectra of Saturn’s rings (Fig. 15.33) and has no strong IR absorptions. Nanohematite has muted spectral features compared to larger grained hematite, due to crystal field effects at grain surfaces and the high surface to volume ratio when the particles are less than a few tens of nanometers in diameter (Morris et al. 1985). Clark et al. (2008b, 2009) have used combinations of nanohematite and carbon or fine-grained metallic iron to model the spectra of various of Saturn’s icy satellites, and showed that admixture of un-oxidized fine-grained iron along with the (oxidized) nanohematite led to improved fits across the entire visual range. Analog laboratory spectra indicate that nanohematite abundance of only 0.25 wt% is needed to match spectra of the Cassini Division and C-ring, the more heavily contaminated rings. Less nanohematite might be needed to explain spectra of the A and B rings because less dark material is contaminating those rings, allowing increased multiple scattering within the regolith. Such small abundances of nano-hematite (very fine-grained hematite or Fe_{2}O_{3}) is a strong UV absorber that matches the spectral structure observed in spectra of Saturn’s rings (Fig. 15.33) and has no strong IR absorptions. Nanohematite has muted spectral features compared to larger grained hematite, due to crystal field effects at grain surfaces and the high surface to volume ratio when the particles are less than a few tens of nanometers in diameter (Morris et al. 1985). Clark et al. (2008b, 2009) have used combinations of nanohematite and carbon or fine-grained metallic iron to model the spectra of various of Saturn’s icy satellites, and showed that admixture of un-oxidized fine-grained iron along with the (oxidized) nanohematite led to improved fits across the entire visual range. 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Fig. 15.33 (a, left): Photo of hematite showing its redness as a solid and suspended in water. (b, right): Laboratory analog models with metallic iron, nano-hematite, carbon black, and water ice are compared to VIMS spectra of the C-ring and Cassini Division. The Cassini Division VIMS spectrum is from S42, Rev 75 LATPHASE00, Phase Angle = 19 degrees, a 41 pixel average, and the C-Ring VIMS spectrum is from the same observation, Phase Angle = 19 degrees, a 69 pixel average. Spectra A-D are laboratory analogs all at 84–90 K at a phase angle of 20 degrees and have been scaled close to the rings spectra to illustrate varying UV absorber and NIR slopes. A) H_{2}O + 2% (75:25 nano-iron (metallic): nano-hematite), B) H_{2}O + 1% (75:25 nano-iron (metallic): nano-hematite), C) H_{2}O + 0.25% nano-hematite + 0.25% carbon black + 33% metallic iron <10 \mu m, and D) H_{2}O + 0.5% carbon black + 0.25% nano-hematite. The nano-metallic iron and nano-hematite samples contain approximately 100 nm diameter particles. Particles much smaller than the wavelength of visible light produce NIR blue slopes while the addition of larger grains of metallic iron produces NIR red slopes in agreement with the ring observations. Clark et al. (2008b) argue that the amount of metallic iron in the ring particles could be 10–30 times smaller than in the sample shown here (to avoid violating microwave observations; Chapter 2), if finer grained iron were used instead of the <10 \mu m grains shown here
nanohematite would not perceptibly add to the 3 μm ice absorption, but could slightly decrease the contrast in the 2.6–2.86 μm region, making the mixture better fit the ring data than pure ice (see Fig 15.26). This is because the ice index of refraction is so low at 2.86 μm that trace contaminants increase the reflectance, while the 2.6 μm reflectance will remain little changed. This possibility might suggest that the ring redness reflects an extrinsic, rather than an intrinsic, material (see Section 15.5.6). The pros and cons of the hematite, tholin, and PAH options are discussed further in Section 15.6.3.

15.4.9 Comparison of Ring Spectral Properties with Other Icy Objects

Alternate ring origin scenarios have included either regular Saturnian moons, or interlopers from the Kuiper belt, as possible ring parents. In this subsection we present a comparative study of the icy surfaces of the Saturnian system (including rings A, B, C and CD, regular and minor satellites) as well as of some TransNeptunian Objects (TNOs). For this study we selected about 1,500 full-disk observations of both regular satellites (Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus) and minor satellites (Atlas, Prometheus, Pandora, Janus, Epimetheus, Telesto, Calypso and Phoebe) from a wide range of distances, hemispheric longitudes, and solar illumination angles (Filacchione et al. 2007, 2008b). For the main rings, we used an East-West mosaic taken in reflectance by VIMS in high spatial resolution⁶ (Filacchione et al. 2008a). In addition, some Earth-based VIS-NIR spectra of TNOs were considered: 1996TO66 (Brown et al. 1999), 1999UG5 (Bauer et al. 2002), 2003UB313 (Licandro et al. 2006a), 2005FY9 (Licandro et al. 2006b), 90377/Sedna (Barucci et al. 2005) and Triton (Buratti et al. 1994; Quirico et al. 1999; Tryka and Bosh 1999; Grundy and Young 2004; Hicks and Buratti 2004). As in Section 15.4.5 we selected the following indicators: $S_{350=520}$, $S_{520=950}$, BD$_{1.5}$ and BD$_{2.0}$.

Figure 15.34 shows the distribution of $S_{350=520}$ vs. $S_{520=950}$. The ring region clusters are circumscribed to simplify the plot. The highest values of $S_{350=520}$ are observed in the B ring (cyan points); the A ring corresponds to $2.5 < S_{350=520} < 3.0$ (red points), the Cassini Division (CD; green points) contains $1.2 < S_{350=520} < 2.0$ while the C ring (blue points) shows $0.6 < S_{350=520} < 1.1$. For $S_{520=950}$ we observe values $-0.05 < S_{520=950} < 0.3$ in the A and B rings, while the CD and C ring show small but noticeable differences ($-0.15 < S_{520=950}(CD) < 0.1$ and $0.05 < S_{520=950}(C) < 0.25$). Many regular satellites (Tethys, Dione, Rhea, Mimas, Iapetus trailing) have spectral slopes similar to the CD. The C ring is not quite like any of the icy moons. Overall the rings are remarkable in having much higher $S_{350=520}$ than any of the regular satellites, as pointed out by Cuzzi and Estrada (1998). However, Hyperion has $S_{520=950} > 0.5$, redder than any ring region at these long visual wavelengths; in fact Iapetus and Hyperion form an entirely separate branch on this plot. On the other hand, Enceladus and Phoebe have very low $S_{350=520}$, and have a slightly negative $S_{520=950}$. The TNOs we considered have the highest spread in spectral slopes (Sedna and 1999UG5, not shown here, are extremely red compared to Saturnian objects (Barucci et al. 2005; Bauer et al. 2002). 2003UB313 and 2005FY9 have spectral slopes similar to the A ring and to Rhea. Charon and Eris, like Phoebe and Enceladus, are fairly neutral. Triton seems to have a spectrum that varies with time (Fig. 15.35); in its most neutral appearance it is compatible to the C ring; at its reddest, it is comparable to the A and B rings (Hicks and Buratti 2004).

The principal spectral indicators in the IR range are the water ice band depths at 1.5 and 2.0 μm (respectively BD$_{1.5}$ and BD$_{2.0}$). Figure 15.36 shows a scatter plot of these two band depths. In this case the observed points are dispersed along two well-defined diagonal branches. The upper branch contains the ring points, which reach the largest BD$_{1.5}$ ($>0.6$) and BD$_{2.0}$ ($>0.7$) in the A and B rings. On each branch, the fractional abundance of non-icy contaminants decreases from lower left to upper right. The CD and C rings are grouped towards the faintest ice band strengths. A similar distribution is found for the icy satellites, which are grouped on a second branch characterized by lower BD$_{2.0}$ with respect to the rings. Pandora and Prometheus more closely follow the ring trend than the satellite trend. The more pure water ice objects are at one extreme of this branch (Enceladus and Tethys at BD$_{1.5} > 0.5$, BD$_{2.0} > 0.65$) and the least pure at the other extreme (Phoebe and Iapetus (leading side) at BD$_{1.5} < 0.3$, BD$_{2.0} < 0.4$). 1999UG5 and Triton are compatible with Iapetus (leading side) while Sedna has very weak water ice bands. The fact that some TNOs have unobservable water ice bands does not mean that water ice is absent in them, but more plausibly that it is simply obscured by thick surface layers of more volatile material such as methane, nitrogen, etc.

Finally, in Fig. 15.37 we show the distribution of BD$_{1.5}$ vs. BD$_{2.0}$. We have combined results from both east and west ansae in the S36-SUBML001 VIMS mosaic. We see several diagonal branches, with that containing the C ring and Cassini Division being the most dramatic, trending upwards from their inner portions which connect to several satellites, to their outer portions which connect to the A and B rings. The A and B rings have the highest values of both

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⁶ (LATPHASE001 in sequence S14 - VIS IFOV 166 x 166 μrad, IR IFOV 250 x 500 μrad, with exposure times of 5.12 sec (VIS) and 80 msec (IR) from a distance of about 1,400,000 km from Saturn (inclination angle = 16°, phase = 51°)
Fig. 15.34 Scatter plot of the 0.35–0.52 (S_{350–520}) vs. 0.52–0.95 μm (S_{520–950}) spectral slopes measured by VIMS on ring, Saturnian icy satellite, TNOs and Triton. The A and B rings are characterized by the highest S_{350–520}, denoting the reddest visible spectra at short wavelengths. The ring scatter plot is circumscribed for clarity.

Fig. 15.35 Triton’s visual wavelength spectrum is the closest outer solar system analog to that of the rings, being steep at short wavelengths and fairly flat at long wavelengths. This figure shows Triton’s (variable) visible spectra at a number of epochs from 1997 to 2000 (Hicks and Buratti 2004) compared with B and C ring spectra from VIMS (black lines) and an HST average ring spectrum by Karkoschka (1994, red line) with which HST spectra by Cuzzi et al. (2002) are in good agreement. Whether the difference between the VIMS B ring spectrum and the Karkoschka spectrum in the 680–950 nm range is real, or a calibration issue, merits further study.
Fig. 15.36 Scatterplot of the water ice 1.5 and 2.0 μm band strengths (BD$_{1.5}$ vs. BD$_{2.0}$) as measured by VIMS on rings (plus signs) and various positions on the Saturnian icy satellites (dots), along with comparable properties measured from Earth on TNOs and Triton. Inset: classification map of the water ice band depths across the rings.

Fig. 15.37 Scatterplot of the $S_{350-520}$ spectral slope vs. the water ice band strength at 1.5 μm (BS$_{1.5}$) as measured by VIMS on rings (plus signs) and various locations on the Saturnian icy satellites (dots), along with comparable properties measured from Earth on TNOs and Triton. The A and B rings have the reddest slope while maintaining a high 1.5 μm band strength.
15.5 Ring Atmosphere and Meteoroid Bombardment

15.5.1 Introduction

Saturn’s extensive ring and satellite system is exposed to the ambient photon radiation field, the magnetospheric plasma, and meteoroid flux. These cause ejection of surface material, producing a toroidal gaseous envelope. Although the highest neutral densities are over the main rings, scattered atoms and molecules from the ring atmosphere extend from Saturn’s atmosphere to beyond Titan’s orbit (Johnson et al. 2006a; Fig. 15.38). This extended ring atmosphere is superimposed on a large toroidal atmosphere produced primarily by direct outgassing of water molecules from Enceladus (Johnson et al. 2006b) and, to a lesser extent, by the sputtering of the icy satellite surfaces and the grains in the tenuous E, F and G rings. The combined toroidal atmosphere is dominated by water products: H2O, OH, O, H, H2 and O2 and their ions. This toroidal atmosphere is the principal source of plasma in Saturn’s magnetosphere and, possibly, the principal source of oxygen for the upper atmospheres of both Saturn and Titan. However, the dominant molecular components from the two largest sources differ. Enceladus primarily outgases H2O with trace amounts (~4%) of carbon and nitrogen species (Waite et al. 2006), while the atmosphere over the main rings appears to be dominated by molecular oxygen (Johnson et al. 2006a).

15.5.2 Main Rings

A plasma has been reported containing O2+ formed from O2 that is produced in and ejected from the surfaces of icy ring particles (and satellites; e.g., Johnson and Quickenden 1997). It was initially discovered by the CAPS (Cassini Plasma Spectrometer) instrument at SOI along Cassini’s trajectory over the main rings from ~1.82 to 2.05 Rs (Tokar et al. 2005) and since studied from ~4 to 12 Rs (Martens et al. 2008; Tseng et al. 2009); see Figs. 15.38 and 15.39. In addition, during SOI, INMS detected H+, O+, and O2+ in proportions of 1.0:0.3:1.0 over the A ring from ~ 2.05 to 2.23 Rs. They reported an O2+ density at ~2.2 Rs of ~0.1–1 cm−3 and a very rough upper limit of ~105 neutrals cm−3 (Waite et al. 2005). INMS also detected bursts of molecular hydrogen ions over the A ring. Although H2+ must be present at some level, it has yet to be determined whether these observations were due to transients in the ring atmosphere, impacts of grains onto the instrument, or an artifact due to surface desorption within the instrument.

Since ions and electrons are efficiently absorbed by ring particles, the energetic particle flux is very small over the main rings and is dominated by a low flux of energetic ions produced by cosmic ray impacts (Cooper 1983). Therefore, the plasma-induced decomposition and sputtering rate are both very small. Carlson (1980) estimated the UV photodesorption of water molecules into the ring atmosphere as also being negligible. Meteoroid bombardment probably dominates the initial production of the vapor environment of the rings (Morfill 1983). An interplanetary value of 3 × 10−17 g cm−2 s−1 gives a two-sided flux at the rings

S_{350–520} and BD_{1.5}. The B ring separates into at least two differently sloped structures: the upper branch contains points in the outer B ring (R > 105,000 km) while the lower branch contains points in the inner B ring (R < 105,000 km). The CD has intermediate values. Epimetheus, Dione, and Hyperion overlay the innermost C ring in this plot. Mimas, Enceladus, Tethys, Pandora and Prometheus differ from the ring primarily in their higher ice BD at the same color. Iapetus, Phoebe, 1995UG5 and Triton have lower BD. Sedna has the highest S_{350–520} and the smallest BD_{1.5}, being primarily covered with methane. In fact, it is notable that, while the TNO data are sparse, a trend can be detected which groups all the TNOs (upper left to lower right) which is nearly orthogonal to the trend of the ring properties (in which redness increases with water ice band depth).
of about $2.5 \times 10^{-16} \text{ g cm}^{-2} \text{ s}^{-1}$, after adjusting for gravitational focussing (Cook and Franklin 1970; Ip 1984; Cuzzi and Durisen 1990) and a water vapor production rate $\sim 5 \times 10^6 \text{ H}_2\text{O cm}^{-2} \text{ s}^{-1}$ ($\sim 10^{27} \text{ H}_2\text{O s}^{-1}$ averaged over the ring system; Ip 1984; Pospieszalska and Johnson 1991). Because the emitted H$_2$O molecules re-condense on ring particles, the average column density ($\sim 10^{11} \text{ cm}^{-2}$) is much lower than the O$_2$ column densities at SOI ($> 2 \times 10^{12} \text{ O}_2 \text{ cm}^{-2}$). A meteoroid flux at the rings as large as $5 \times 10^{-14} \text{ g cm}^{-2} \text{ s}^{-1}$ (Ip 2005) would result in $\sim 10^9 \text{ H}_2\text{O cm}^{-2} \text{ s}^{-1}$ ($\sim 10^{29} \text{ H}_2\text{O s}^{-1}$ averaged over the ring system), and would lead to a density of water ions comparable to that detected for O$_2^+$. The lack of definitive detection of water ions would suggest fluxes that are at least an order of magnitude smaller. Arguments in Cuzzi and Estrada (1998) and Cuzzi et al. (2002) allow an upper limit of $\sim 3 \times 10^{-15} \text{ g cm}^{-2} \text{ s}^{-1}$ at the rings, even assuming a large gravitational focussing factor of 40 (an order of magnitude high for projectiles on highly inclined or eccentric orbits).

Ip (1995) suggested that photo-dissociation products from such a primary water atmosphere could react to produce O$_2$. Since O$_2$ would not condense out at the temperatures of the ring particles, it could accumulate in the ring atmosphere. Based on a surface source of H$_2$O$\sim 5 \times 10^{27} \text{ s}^{-1}$, he predicted a tenuous atmosphere $\sim 5 \times 10^{11} \text{ O}_2 \text{ cm}^{-2}$, about an order of magnitude smaller than inferred from SOI data. In addition however, the incident UV flux can decompose solid water ice, producing H$_2$ and O$_2$ directly (Johnson and Quickenden 1997). Therefore, although photodecomposition of ice is not a very efficient process, O$_2$ and H$_2$ are directly supplied to the ring atmosphere on the illuminated side. Since ejected water molecules and their dissociation products will stick on re-impacting the ring particles, but the H$_2$ and O$_2$ formed by decomposition do not, an atmosphere containing H$_2$ and O$_2$ can accumulate (Johnson et al. 2006a). At equinox, production from an impact-generated H$_2$O atmosphere may provide a low residual O$_2$ ring atmosphere at the level predicted by Ip (2005).

15.5.3 Modeling of the Ring Atmosphere

Laboratory experiments in which ice is exposed to a Lyman-alpha photo-flux (Westley et al. 1995) show that O$_2$ and H$_2$ are directly produced by the solar EUV/UV flux at an estimated rate $> 10^6 \text{ O}_2 \text{ cm}^{-2} \text{ s}^{-1}$ (Johnson et al. 2006a). Using the CAPS data and this source rate resulted in a number of simulations of the formation and structure of the ring atmosphere (Johnson et al. 2006a; Bouhram et al. 2006; Luhmann et al. 2006; Farmer and Goldreich 2007; Tseng et al. 2009). These simulations also predict the abundance of neutral molecules needed to produce the observed ions. The results from one set of simulations (Fig. 15.40) gives estimates of the spatial distributions of O$_2$, O$_2^+$, and O$^+$ above and below the ring plane. The essence of these simulations and their implications for the Saturnian system are given below.

Since the O$_2$ and H$_2$ produced by photolysis (primarily on the lit side of the rings) do not condense out, they orbit with and thermally equilibrate with the ring particle surfaces. Therefore, O$_2$ atmospheres exist both north and south of the ring plane with slightly different scale heights due to the different surface temperatures of the ring particles ($\sim 0.025 \text{ R}_S \sim 1.500 \text{ km at } \sim 2 \text{ R}_S$). A corresponding H$_2$ atmosphere is also produced in such a model, having a scale height about 4 times larger (Johnson et al. 2006a). The instantaneous O$_2$ and H$_2$ column densities are limited by their destruction rates, primarily photo-dissociation. Since the O and H produced by dissociation have excess energy, they are rapidly lost to Saturn, ionized in the magnetosphere, or re-impact and stick to ring particle surfaces. However, because of the significant mass difference, hydrogen is lost preferentially.

Ions are formed from the orbiting neutrals primarily by photo-ionization: O$_2$ + hv $\rightarrow$ O$_2^+$ + e or O + O$^+$ + e in about a 4:1 ratio. These freshly produced ions are then “picked-up” (accelerated by Saturn’s advective electric field). Because the ions are formed by photolysis, at the time of SOI the production rate south of the ring plane was larger than north of the ring plane. The O$^+$ are formed with additional energy, but the O$_2^+$ are not. Therefore, the molecular ions are picked-up...
with a velocity that is primarily perpendicular to the magnetic field and will oscillate about the magnetic equator. However, the magnetic equator is ~0.04 Rs north of the ring plane, a distance larger than the O$_2$ scale height (~0.025 Rs). Thus the for the A and B rings, a denser O$_2^+$ atmosphere will be found preferentially north of the ring plane, and a seasonal variation would be anticipated once the sun again illuminates the north face of the rings (Tseng et al. 2009). Newly formed ions can be absorbed by ring particles as they move along the magnetic field lines attempting to cross the ring plane. In the modeling results of Fig. 15.40, the absorption probability is determined by the local optical depth; thus, abundances are higher above locations crossing the optically thin Cassini Division.

The nature of the ion pick-up process changes closer to Saturn. For equatorial distances from Saturn > ~1.86 Rs (the corotation radius) the rotation speed of the magnetic field, which guides the motion of the ions, is larger than the average speeds of the neutrals as they orbit. The opposite is the case when R < ~1.86 Rs, so that freshly ionized neutrals are typically slowed by the magnetic field. This slowing, combined with Saturn’s gravity, can cause ions formed well within ~1.86 Rs to precipitate along the field lines into Saturn’s southern atmosphere (Northrop and Hill 1983; Ip 1984; Luhmann et al. 2006, Tseng et al. 2009) as indicated by the 2nd panel in Fig. 15.40. Plasma loss to Saturn’s atmosphere results in the net erosion of the ring particles and becomes the dominant ion loss process for the inner ring system. On ionization, neutrals ejected from particles in the low-optical depth C ring are lost with an especially high probability to impact the rings. However, ions formed inside 1.86 Rs, especially those produced on the southward side, escape to the planet (see flux at lower left of right hand figure). Figure courtesy W. Tseng; see also Tseng et al. (2009).

15.5.4 Atmosphere-Driven Chemistry on Icy Ring Particle Surfaces

One of the principal uncertainties in modeling the ring atmosphere and ionosphere is the fate of radicals and ions when they impact the ring particle surfaces. H$_2$ and O$_2$ only briefly adsorb on the surface, becoming thermally accommodated to the surface temperature before they return to the gas phase. The radicals (O, H) and ions (O$_2^+$, O$^+$, H$_2^+$ and H$^+$) either stick or react. Since hydrogen is preferentially lost from the system, the ring particle surfaces are, on average, slightly oxidizing as discussed elsewhere for Europa’s surface (Johnson et al. 2004) and also likely charged. In addition, the returning O$_2^+$, O$^+$ and O are reactive. Johnson et al. (2006a) obtain agreement with CAPS ion data by requiring that a significant fraction of the returning oxygen reacts on the surface and returns to the atmosphere as O$_2$. This was also suggested by Ip (2005). This recycling resulted in roughly an order of magnitude increase in the densities and loss rates (Section 15.5.5). Based on the above, the surface chemistry is such that non-water ice contaminants would tend, on average, to become oxidized as is the case at Europa where the principal contaminants (sulfur and carbon) are observed primarily as oxides. Therefore, near-surface, refractory carbon species, such as hydrocarbons, tholins, or PAHs, would
likely experience reactions in which they would be degraded and oxidized to form volatiles such as CO and CO$_2$ in ice. The most volatile product (CO) would, like the O$_2$ formed, be desorbed. It also would not recondense, and would be eventually scattered from the ring atmosphere, removing surface carbon. Near-surface CO$_2$ can also be photolyzed, producing CO, which can then be lost. In laboratory experiments NH$_3$ in ice mixtures is rapidly destroyed by EUV photons (Wu et al. 2006) and, since it is more volatile than H$_2$O, its lifetime on the surface of a grain is not long. In addition, it can form N$_2$ under irradiation (e.g., Johnson 1998; Loeffler et al. 2006), which could be trapped in inclusions, like O$_2$ at Europa (Johnson et al. 2004), or it can diffuse out and be removed like O$_2$ (Teolis et al. 2005) With the removal of volatiles, more refractory species and/or heavy oxides (such as carbon suboxides) should be preferentially seen in the surface. Similarly the returning oxygen can interact with Fe, either as metal or some other reduced state, forming an iron oxide; Fe$_2$O$_3$ has been suggested to help explain the ring reflectance data (Section 15.4.8).

15.5.5 The Ring Atmosphere as a Magnetospheric and Atmospheric Source

Because the O$^+$ ions are formed with a significant, randomly oriented energy, they will have a distribution in velocity large enough for a fraction of them to reach the spacecraft altitude. On the other hand, O$_2^+$ is formed with no additional kinetic energy. Therefore, the O$_2^+$ detected at altitudes $>0.1$ Rs must have been scattered by collisions with neutrals in the ring atmosphere (Johnson et al. 2006a). Farmer and Goldreich (2007) examined the collisional interaction between the neutral and the ion component of the ring atmosphere to constrain the estimates of density of the atmosphere and ionosphere, as suggested by models of the ring spoke phenomenon (Morrill and Thomas 2005); however, their upper limit of $\sim2 \times 10^{15}$ O$_2$ cm$^{-2}$ did not improve the estimates based on models of the Cassini ion data (Johnson et al. 2006a).

Whereas the motion of a scattered ion is restricted by the magnetic field, neutrals are subject only to gravity and their centripetal motion. Therefore, they can be scattered into Saturn’s atmosphere or into the Saturnian magnetosphere beyond the edge of the main rings forming an extended ring atmosphere as simulated in Fig. 15.40. Ionization of the O$_2$ in the extended ring atmosphere contributes to O$_2^+$ detected outside of the ring system (Tokar et al. 2005; Young et al. 2005; Martens et al. 2008). Based on a Monte Carlo model (Tseng et al., 2009), about $5 \times 10^{26}$ O s$^{-1}$ are scattered out of the ring atmosphere for the illumination at SOI, either as O or O$_2$. Most of these are in large orbits which eventually re-impact the ring particles. A small fraction is ionized as they orbit in the magnetosphere, about 0.4% escape and about 6% are scattered into Saturn’s atmosphere (Johnson et al. 2006a; Tseng et al. 2009). This gives an O source rate $\sim10^5$O cm$^{-2}$ s$^{-1}$ which is about an order of magnitude smaller than the required flux ($\sim4 \times 10^6$O cm$^{-2}$ s$^{-1}$; Moses et al. 2000, Shimizu 1980, Connerney and Waite 1984; Moore et al. 2006; Moore and Mendillo 2007). Based on the numbers in Johnson et al. (2006a), the oxygen contribution by direct ion precipitation into Saturn’s atmosphere is even smaller: $\sim0.2 \times 10^5$O cm$^{-2}$ s$^{-1}$ as O$^+$ or O$_2^+$. These rates can be up to an order of magnitude larger depending on how oxygen from impacting O, O$^+$ and O$_2^+$ is recycled on the grain surfaces (Johnson et al. 2006a, Ip 2005). Moses et al. (2000) suggested a direct meteoroid flux into Saturn’s atmosphere of $\sim3 \pm 2 \times 10^{-16}$ gm cm$^{-2}$ s$^{-1}$ which could explain its atmospheric oxygen; this is consistent with estimates of direct meteoroid infall by Cuzzi and Estrada (1998), and, given the inadequacy of the indirect flux from the ring atmosphere, constitutes an independent method of estimating meteoroid flux.

Neutrals scattered from the ring atmosphere can be ionized and contribute to the magnetospheric plasma outside of the main rings (e.g., Fig. 15.38). Initially the toroidal atmosphere of water dissociation products seen by HST (Shemansky et al. 1993) was thought to be derived from the E-ring grains. However, Jurac et al. (2002) showed that the principal source region was near the orbit of Enceladus, and Cassini eventually identified this source as outgassing from Enceladus’s south polar region (Waite et al. 2006; Hansen et al. 2006), which is also the source of the E-ring grains. Cassini data have also shown that inside the orbit of Rhea there is a dearth of the energetic particle radiation that is the source of molecular oxygen at Europa and Ganymede (Johnson et al. 2004). Since the Enceladus plumes and sputtering primarily supply water products to the plasma (H$^+$, O$^+$, OH$^+$ and H$_2$O$^+$), and O$_2$ is hard to create in the magnetosphere, the ionization of neutral O$_2$ originally produced in the ring atmosphere is the primary source of O$_2^+$ inside the orbit of Rhea (e.g., Fig. 15.38). Therefore, the plasma measurements of O$_2^+$ give a clear marker for the extent of Saturn’s ring atmosphere.

15.5.6 Meteoroid Bombardment, Ring Mass, and Ring Composition

The subject of meteoroid bombardment is reviewed in detail by Chapter 17, so we will only mention several aspects relating to ring compositional properties. The rings are constantly bombarded by primitive interplanetary meteoroids,
which move mass around and pollute the rings with considerable amounts of silicate and carbonaceous material, changing the reflectivity and color of the dominantly icy ring particles. In this scenario, regions with small mass density (C ring and Cassini Division) are expected to be – and are seen to be – characterized by lower particle albedos and more neutral colors (Cuzzi and Estrada 1998). Recent VIMS results showing a smooth variation of water ice band depth across the abrupt inner A and B ring boundaries (Section 15.4.5) are also consistent with these models. Extension of the models, along with refinement of their parameters, has some promise to constrain the “exposure age” of the rings; best current estimates of this scenario give a ring age on the order of several hundred million years, about one-tenth the age of the solar system. The most significant uncertainties in the inferred ring age derive from the incoming mass flux of meteoroids, and the surface mass density of the rings. Some recent suggestions have arisen that the ring “exposure age” might be much greater, if the surface mass density were much larger than currently inferred, or if the incoming mass flux were much smaller (or both).

Ring surface mass density: In order for some ring region to avoid becoming polluted over 4.5 Gyr at the currently estimated meteoroid mass flux, it must have a much larger unpolluted mass reservoir cloistered away somewhere, upon which to draw occasionally (see Chapter 17; also Esposito 2008). In the A ring, the mass density has been measured to be about 40 g cm$^{-2}$ by dozens of spiral density waves that cover nearly its entire radial extent (see Chapter 13), consistent with the observed ring particle size distribution (Section 15.2). Compared to this, the mass of both the visible embedded moonlets Pan and Daphnis, and that of the indirectly observed 100 m radius “propeller” shards (Section 15.3), is insignificant. Thus there is no reason to believe the A ring has any unseen reservoir from which to replenish it with fresh material. Neither is the surface mass density of the inner B ring likely to be greatly in error; the Janus 2:1 density wave propagates across 600 km of radial extent; Holberg et al. (1982) and Esposito et al. (1983) give the mass density in this region as 70 g cm$^{-2}$, consistent with observed optical depths and ice particles of several meter upper radius limit. There is a single estimate of mass density in the outer B ring, from a bending wave in a complex region (Lissauer 1985), giving 54 ± 10 g cm$^{-2}$, which is consistent with canonical particle sizes and local ring optical depth. Like the A ring, these parts of the B ring seem to have no unseen mass reservoirs.

This leaves us with the dense central core of the B ring (see e.g. Fig. 15.1b, regions B2 and B3, and Chapter 13). Here, it is difficult to place an upper limit on the mass density, as no waves or wakes have been found. If this opaque and largely unexplored region is the only place where large amounts of excess mass are secluded, it then becomes a puzzle why its color and brightness are not more different from the color and brightness of the adjacent inner B ring, where the surface mass density is in a range which should be darkened considerably by meteoroid bombardment over the age of the solar system. That is to say, if there were a huge contrast in surface mass density between the inner/outer and central B rings, allowing only the central B ring to be primordial, there should be a strong change in particle color and brightness between these regions of such greatly differing mass density, which is not seen. Cassini will attempt dedicated observations of the ring mass (Section 15.6.4).

Meteoroid mass flux: Cuzzi and Estrada (1998) reanalyzed prior analyses of the meteoroid mass flux, and favor a value of 4.5 × 10$^{-17}$ g cm$^{-2}$ s$^{-1}$ for the incoming, unfocussed, one-sided mass flux. Using this value they, and Durisen et al. (1992, 1996) arrived at ring exposure ages in the range of a few hundred million years. The density of the ring atmosphere (Section 15.5) was once thought to constrain the meteoroid mass flux; however, its high density and surprising O-rich composition suggests that meteoroid bombardment is not in fact the driving mechanism except perhaps at solar equinox when photo-desorption ceases. The value of the mass flux in the jovian system was addressed by the Galileo spacecraft (Sremcevic et al. 2005), using measurements of the “albedo” dust mass ejected into the Hill spheres of several of the jovian satellites. Their conclusion (cf. their Section 4.4) was that the unfocussed, one-sided mass flux at Jupiter was 3 × 10$^{-17}$ g cm$^{-2}$ s$^{-1}$. If the mass flux in the jovian planet region is primarily cometary and Kuiper-belt related, the value at Saturn is not likely to be significantly different, so this measurement somewhat supports the current best estimate noted above. Cassini will attempt dedicated observations (Section 15.6.4).

15.6 Summary, Discussion, and Future Directions

15.6.1 Summary of Observational Properties

Cassini observations are only in the very early stages of analysis, because many of the investigators remain deeply involved in design of ongoing and future observations; thus, this chapter represents only a progress report on what will be a decades-long study. More in-depth studies, new data, and even calibration refinements might change some results and inferences reported here.

Ring particles are likely to be chunky aggregates of smaller particles (Section 15.2), with permanence that remains unknown. They are surely obliterated frequently by
incoming meteoroids of various sizes. Several lines of argument (phase function at low phase angles, radar reflectivity) suggest the observed particles, or aggregates, are highly irregular, in the nature of dense grape clusters rather than spheres. Scattering properties indicate that these particles, or aggregates, obey a rough powerlaw with a fairly sharp upper cutoff size; both lower and upper cutoff sizes vary somewhat with location (Section 15.2.9). These “particle entities” do seem to be smaller than “wakes” as observed by UVIS (Section 15.2.10). The area fraction of tiny dust grains in the main rings is generally small. The particle size distribution is not a strong constraint on the origin and evolution of the rings, rather being determined by local collisional dynamics (Chapter 14). However ring particles (and self-gravity wakes) seem to contain most of the ring mass in, at least, the A and inner B rings.

**Ring composition:** The primary composition of the rings is water ice; it is quite pure and predominantly crystalline, to the sensitivity level of the measurements (there is probably less than a few percent amorphous ice, if any). The reddish color of the rings at wavelengths shorter than 500 nm testifies to a non-icy component which is strongly absorbing at near-UV and blue wavelengths, which must represent less than a few percent by mass in order not to violate microwave brightness observations (Chapter 2). The detailed shape of the spectrum between 600–900 nm differs slightly between Cassini and HST observations, perhaps due to calibration uncertainty. There appears to be no CO₂ or CH₄ in the rings. There is no sign of spectral features in the 3.3–3.5 μm region that would give supporting evidence for C-H organics; however, this feature is intrinsically quite weak in many tholins and its absence does not preclude reddish organics or PAHs (Section 15.4.8). An alternative compositional interpretation for the UV absorber is nanohematite. Nanohematite is a strong UV absorber and has no other strong spectral features in the 1–5 micron spectral range, consistent with high-signal-to-noise-ratio VIMS spectra. The presence of hematite is consistent with oxidation of nanophase iron particles by highly oxidizing particle surfaces, a result of the oxygen atmosphere around the rings (Section 15.5). To date, there is no clear spectral evidence for silicates. Regolith grain sizes on the surfaces of ring particles have been inferred from near-IR and far-IR observations; different regolith radiative transfer models lead to at least factor-of-two different grain sizes (Section 15.4.7).

**Radial composition variations:** Ring composition varies from place to place in systematic ways that are obviously, but not directly, correlated with local surface mass density and/or optical depth. This variation is inferred from radial variations of ring color, particle albedo, and water ice band depth (Section 15.4.5). The C ring and Cassini Division are more contaminated by non-icy material than the A and B rings, but the composition of this pollution remains uncertain (see however Fig. 15.11 for intriguing behavior in the Cassini Division and C ring near 1 μm). The degree of visual redness (caused by some UV absorber) is highly correlated with ice band strengths, suggesting the UV absorber is distributed within the ice grains rather than as a distinct component. More detailed mixing models should be explored. The radial profile of 340–440 nm redness is slightly, but clearly, distinct from that of 440–550 nm redness, and the radial profile of 500–900 nm spectral slope is entirely different and uncorrelated with water ice band depth (Figs. 15.22–15.24). In fact, the most plausible extrinsic pollutant – material found in the C ring and Cassini division – is less red at short visual wavelengths – where the main rings are most dramatically red, and more red at long visual wavelengths than the A and B ring material. These distinct radial variations point to several different processes and/or contaminants with different radial distributions – some perhaps representing primordial or intrinsic properties and some representing extrinsic or evolutionary influences.

### 15.6.2 Origin – the Big Picture

**Formation and compositional evolution:** The rings are under the influence of vigorous evolutionary processes (satellite torques, meteoroid bombardment, and perhaps ring-atmospheric chemistry) that reshape their structure and change their composition on timescales which are apparently much shorter than the age of the solar system. The rings are very pure (>90%) water ice, requiring their parent to have differentiated significantly from a primitive solar mix (roughly equal proportions of ice, silicate, and refractory carbon compounds). Post-Voyager interpretation of this combination of factors suggested that the rings are the secondary product of the destruction of a differentiated body, occurring well after the time the Saturn system formed, rather than some primordial residue formed in place at the time of Saturn’s origin (Section 15.5.6). Whether some or all parts of the main rings can be as old as the solar system is a question for which Cassini hopes to provide the answer, before the end of its mission (Section 15.6.4).

**Where did the ring parent come from?** Regardless of the formation epoch of the rings, one still needs to distinguish between the birth location of the ring parent(s). That is, the rings can be connected with two alternate formation hypotheses: disruption by impact of a locally formed inner regular satellite, and disruption by tides and collision of some remotely formed, heliocentric interloper (Chapter 17). The probability of either of these events happening significantly after the era of the “late heavy bombardment” (ca. 3.8 Gya) is only about 0.01 (Dones 1991, Chapter 17). Below we assess these two alternate scenarios in terms of known ring
properties and processes, and the properties of parent bodies from these candidate source regions.

(1) Saturn system icy bodies: We immediately limit our view to the regular satellites; the (probably captured) irregular satellites never differentiated, have very low albedo, and are not candidate parents for Saturn’s rings. By comparison, the rings of Jupiter, Uranus, and Neptune are far less massive, and seem to be composed of very dark material so are simple to explain by disruption of small, primitive bodies (Colwell and Esposito 1990, 1992, 1993). Saturn’s regular satellites, on the other hand, are at least ice-mantled and many of them are largely ice in bulk (Iapetus for instance; Chapters 18 and 20). The regular satellites probably formed in some kind of circumplanetary disk (Canup and Ward 2002, 2006; Mosquera and Estrada 2003a,b; Estrada and Mosquera 2006; also Chapter 3). There are ways in which these disks – if they were gas rich (Estrada and Mosquera 2006) – might have become enriched in water ice relative to cosmic abundances, but achieving the enormous amounts characterizing the rings remains an unmet challenge.

Saturn’s regular satellite surfaces generally have spectra that are qualitatively similar, but quantitatively different, from the spectra of the rings. All have deep, crystalline ice bands in the 1–3 μm range. All have red spectra from 340–520nm and fairly flat spectra from 520–950nm (see Fig. 15.34). The main difference from an overall spectral standpoint is that the ring spectra are much redder from 340–550nm than the satellite spectra. The rings lack CO2, as do most of the regular satellites; however, see Section 15.5 regarding its local destruction. Only Phoebe (an obvious interloper), the dark regions of Iapetus (covered with possibly extrinsic material), and Hyperion (a mystery in all regards) show strong CO2 while the signature on the inner large satellites is weak or nonexistent. Spectrally then, the rings share a number of properties with those regular moons that are most plausibly locally formed. The primary difference between the rings and the regular moons is the larger amount of “UV absorber” in the rings (which provides their much steeper 330–550 nm spectral slope).

The lack of typical cosmic abundances of silicates in most of the main rings requires a coreless parent, or a way of segregating the core of a parent and keeping it from becoming increasingly fragmented and mixed into the rubble of the rings. Could Pan and Daphnis be such primordial shards? Any primordial shards would probably be deeply buried in icy ring material today and their composition unknown (Porco et al. 2008). No moonlets even close to the size of Daphnis have been detected in any other empty gaps, in spite of dedicated searches by the Cassini ISS team. Could the enigmatic, nearly opaque, central B ring hide larger shards, overwhelming their attempts to clear gaps about themselves (Chapter 13)? Indeed there are two fairly narrow, relatively clear radial bands in the densest part of the B ring (Chapter 13). More careful searches for B ring “propellors” in these regions would be valuable. Formation of the rings by destruction of a local differentiated parent would be problematic unless all the silicate core remained in large fragments which have been not only hidden from our view, but also protected from subsequent disruption over subsequent aeons (e.g., Colwell and Esposito 1990, 1992, 1993) by shrouds of enveloping icy material. It seems to us that keeping core silicates out of the current rings represents a serious challenge to ring parentage by disruption of a locally formed and differentiated moon.

(2) Icy denizens of the outer solar system: In this group we include Centaurs, TNOs, and KBOs, which we will collectively refer to as Outer Solar System Objects or OSSOs. Many OSSOs are well known to be “reddish”, with this reddish color generally ascribed to organic “tholins” (Cruikshank et al. 2005). Formation of the rings from such an object would involve dynamical disturbance into Saturn-crossing orbit and close encounter, with tidal or collisionally aided disruption (Dones 1991; Chapter 17). It is believed that Triton incurred a very close encounter with Neptune (and, probably, a collision) that led to its capture; it is also known that Jupiter has tidally disrupted numerous heliocentric passersby; this scenario could be thought of as “Shoemaker-Levy-Triton”. One advantage of this scenario is that the core of the differentiated object could continue on its way, leaving only ice-rich mantle material behind to be captured (Dones 1991, Chapter 17). Looked at more closely, this concept has its own problems. The reddish 340–520nm wavelength spectral properties of most OSSOs persist through the 500–1,000nm spectral range, reminiscent of the properties of Hyperion (see Barucci et al. 2008), and distinct from main ring and (most) icy satellite spectra which flatten at wavelengths longer than 550 nm. However, two of Saturn’s regular moons (Hyperion and Iapetus) have spectra that are strikingly different from the others, and more qualitatively similar to TNOs and Centaurs (Section 15.4.9). On the other hand, Triton itself does apparently have a spectrum that resembles that of the rings, at least during certain observing apparitions (Hicks and Buratti 2004). In the near-IR, other differences become apparent. The most reddish OSSOs have weak (Triton) or nonexistent (Pluto, Sedna, etc.) water ice bands at 1–3 μm wavelengths, instead displaying absorption by CH4, N2, CO (and sometimes CO2). Water is probably present, but presumably coated, perhaps to significant depth, by degassing and freezing of more volatile constituents. The most obviously water-ice rich OSSO (EL61) has a very flat visible wavelength spectrum with no reddening at all (Merlin et al. 2007) – proving that pure water ice actually exists in the outer solar system, even if only on fragments of catastrophic
disruptions! If a reddish, methane-mantled object were to be perturbed into disruption and capture at Saturn, the most volatile material would evaporate over time and the water ice and reddish material might remain behind; however one might expect any CO$_2$ carried in this way to also persist at Saturnian temperatures. Perhaps CO$_2$ is merely a trace surface radiation byproduct on OSSOs rather than a widely mixed component of importance, or perhaps it is quickly destroyed in the ring particle surfaces (Section 15.5).

15.6.3 Candidate “UV Absorbers”

Below we summarize some of the pros and cons of the alternate suggestions that have arisen for the material that provides the steep reddish visual spectra of the rings (and perhaps, to a lesser degree, of the moons as well).

(1) Tholins: It has long been argued that these macromolecular organics, created by the action of diverse energy sources on simple molecules like CH$_4$, NH$_3$, N$_2$, and H$_2$O, are responsible for reddening the surfaces of OSSOs (Cruikshank et al. 2005). Note that the traditional mechanism of radiation reddening of simple ices (see Hudson et al. 2008 for a recent review) produces spectra that are uniformly red out beyond 1 $\mu$m, which is consistent with OSSO colors (Barucci et al. 2008) but not with ring or regular satellite colors (Section 15.4.9). The observed lack of a C-H spectral feature in the 3.5 $\mu$m spectral region of the rings might seem like an argument against the presence of tholin-like red material; however, this feature has never been seen on OSSOs either, and might never be visible in the presence of water ice, because its absorption coefficient at 3.5 $\mu$m is generally less than that of water ice and it is only required in small abundance to explain the red color (Section 15.4.8). Even some pure tholins show no sign of a 3.4–3.5 $\mu$m absorption (Bernard et al. 2006). CO$_2$ and CH$_4$, on the other hand, have relatively large absorption coefficients compared to water at their most detectable wavelengths, so are much more easily seen if present. If CO$_2$ is always formed and present in an environment where tholins are formed and present, then the lack of CO$_2$ in the rings may be an argument against the presence of tholins, whether produced in the Saturn system or carried in by a heliocentric interloper – unless it is quickly destroyed in the ring environment (Section 15.5).

(2) PAHs (organic molecules much smaller than Tholins): Compared to tholins, PAHs are very simple molecules, containing a few, to a few tens, of benzene rings (Salama et al. 1996, Li 2008). Unfortunately, very little is known about their optical properties in bulk or in ice, especially at visual and near-IR wavelengths (Salama et al. 1996 and references therein), but most of them are visually reddish (Fig. 15.32). Their color is related to their physical size, which determines the wavelength of radiation sufficiently short to sense them as conducting/absorbing particles (even if far smaller than the wavelength) (e.g., Schutte et al. 1993, Draine and Li 2001, Mattioda et al. 2005). Photons with energies less than the band gap energy in a PAH (which decreases linearly as its linear dimension increases, vanishing in the “graphite limit”) are less likely to be absorbed; the transition between absorption and lack of it is fairly sharp, so the overall spectrum will depend on the PAH size and structural distribution. The flattening of ring and satellite spectra beyond 550 nm could correspond to the properties of PAHs not much larger than 4–6 rings in linear extent. However, it remains unknown how PAH-forming conditions in the circumplanetary nebula might differ from those of tholins (which seem to be adequately reproduced in lab experiments), and which lead to spectra which continue to absorb to longer wavelengths than seen in the rings, suggestive of larger PAHs. It is possible that disordered tholin structures, containing a random mixture of carbon rings in different lengths and orientations, might also provide just this type of absorption. A speculative possibility is that highly energetic micrometeoroid impacts on the rings process pre-existing graphitic and/or “tholin” material, either in the projectile or in the target particle, into much smaller fragments – the 4–6 ring PAHs of Fig. 15.32, for instance. Impacts are much more intense, and at higher speeds, in the rings than on the surfaces of icy satellites. Some PAHs, or their ionized states common in ice, can display telltale absorption features that are roughly 100 nm wide, at visual wavelengths (Salama et al. 1996 and references therein).

(3) Nanophase iron and nanophase hematite: A number of experimental studies have found that admixture of nanophase hematite and/or iron particles, in extremely small doses, can color icy material reddish (Fig. 15.33) and might help explain some of the ring (and even satellite) spectra. The physics behind this is due to a strong charge transfer absorption extending into the UV. A turnover to relatively neutral behavior is found at about the right wavelength (500 nm). The reddish color of Mars is due to nanophase hematite, for instance (Morris et al. 1985). Nano-hematite particles, moreover, exhibit far less absorption at 850 nm than larger grains (because of their tiny size compared to a wavelength and particle-field effects introduced at that scale), which is relevant because the rings seem to have very little excess absorption at 850 nm, in spite of initial suspicions (Clark 1980) and very careful inspection of the VIMS data by one of us (RC).

Cosmochemically speaking, one expects iron oxides and iron metal to be associated with silicates, rather than ices, and the very low abundance of silicates in the rings suggests a very low abundance of iron metal. Recent in situ observations, however, motivate some openness of mind on the subject. First, during cruise to Saturn, CDA detected
six particles, and measured the composition of two – both iron or iron oxide/carbide and no silicates (Hillier et al. 2007). CDA also detected “stream” particles coming from the ring system (Srama et al. 2006), which were judged to be primarily silicates (Kempf et al. 2005), although the water abundance remains uncertain because of the usually high speed of the impacts (F. Postberg, personal communication 2008). While in Saturn orbit, mostly in the E ring, CDA has predominantly detected ice particles with up to percent-level impurities of silicate, organics or sodium salts, and perhaps 1% by mass of pure iron/iron oxide-or-sulfide particles, which are free of water ice, unlike other non-icy impurities (Postberg et al. 2007, 2008, 2009). So the in situ sampling of particles currently in and around the Saturn system and potentially polluting the surfaces of the rings and satellites, while not yet understood, remains moot on whether iron, silicate, or organic grains are the most important non-icy pollutants. The second surprise was the (O, O₂)-rich ring atmosphere (Section 15.5). Perhaps even a tiny amount of Fe-metal in the ring material could have been oxidized in-situ over the age of the rings to create this unexpected constituent in such abundance. The greater density of the ring O-atmosphere compared to the environment in which the moons reside (Fig. 15.38) might lead to a larger Fe₂O₃ production, and a more extreme 340–520nm redness unique to the rings.

Finally, we note that nano-grains of metal and moderate size PAHs are fairly similar from a physics standpoint – they are both “conductors” with physical sizes smaller – perhaps much smaller - than a wavelength, and might behave similarly from an optical standpoint. More studies of nanophase, conducting absorbers of different composition would be helpful.

15.6.4 Future Work Needing to Be Done

Data Analysis and calibration: First, of course, is a thorough reduction and analysis of ring data regarding size distribution (from stellar and radio occultations) and composition (from UVIS, ISS, VIMS, and CIRS spectra). Only a small fraction of these data, in only a small fraction of observing geometries, have yet been analyzed. Cassini has obtained 2 cm radiometry, with resolution better than the groundbased interferometry that still provides our strongest overall constraints on the abundance of non-icy material (Chapter 2), but only some calibration and preliminary analysis of the data has yet been done. Careful attention must be paid to calibration of all Cassini observations, using available ties to groundbased and HST observations under similar observing conditions where possible.

A new generation of radiative transfer models must be developed and deployed: Inferring composition from remote observations is a multi-stage process. Particle composition is most directly related to particle albedo (as a function of wavelength) by “Hapke”-type regolith radiative transfer models (Section 15.4.6.2). Improved models will need to account for grain size-wavelength similarity, assess the plausibility of nanophase inclusions of profoundly different refractive index than their water ice matrix, and address gross irregularity of the particle aggregate itself. The spectral behavior of contaminants seems to change in significant ways when their sizes decrease into the nano-regime; more experimental data is needed here to provide the optical constants for future modeling efforts. Moreover, different possibilities exist for the configuration and structure in the grainy regolith surfaces themselves: non-icy contaminants can be mixed on a molecular level with ice molecules, or on a grain-by-grain basis; these differences all have physical significance and they make a substantial difference in the inferences of fractional abundances which are derived from modeling – amounting to a systematic uncertainty that is usually overlooked (see, e.g., Poulet et al. 2003).

The structure of the probably very irregular aggregate ring particles (in particular how their facets shadow and illuminate each other) will determine their phase function (Hapke 1984, Shkuratov et al. 2005). The phase function enters into models of the overall ring scattering behavior and is likely to be considerably more strongly backscattering than analogues explored to date (Poulet et al. 2002), and wavelength-dependent as well; Cuzzi et al. 2002). Finally, ring layer radiative transfer models are needed to combine the individual particle albedo and phase function with the effects of multiple scattering and particle volume density to determine the reflectivity of the layer as a function of viewing geometry. It has been shown that traditional “adding-doubling” codes, which assume widely-separated particles, cannot properly match the full range of observations (because of their inability to handle high packing densities) and lead to erroneous, geometry-dependent inferences of particle albedo (Salo and Karjalainen 2003, Porco et al. 2008, Chambers and Cuzzi 2008). On top of all this, we now also know that the rings are not a homogeneous slab, but a two-phase system of gaps and dense clumps (Chapter 13), where the clumps have a preferred orientation! Finally, the ring brightness component due to reflected “Saturnshine” needs to be properly accounted for.

Chemical Evolution models: Models of circumplanetary satellite formation should be improved to include thermal and chemical evolution to track the history of CO₂ (vis-a-vis CO, CH₄, etc.). Moreover, the role of a persistent O₂ atmosphere regarding production of oxidized minerals such as Fe₂O₃ should be considered.
Measure the meteoroid mass flux and the ring mass: During Cassini’s Equinox mission (2008–2010) the spacecraft will fly by Rhea closely to measure the mass flux indirectly, sampling the ejected mass filling its Hill sphere in the approach used by Sremcevic et al. (2005) at Jupiter. The geometry of the flyby will make it possible to distinguish this ejecta from whatever equatorial debris might or might not be responsible for the charged article absorptions observed by MAPS instruments (Jones et al. 2008). At the end of Cassini’s mission, it is hoped that a number of orbits can be implemented with the periapse inwards of the D ring. In these close orbits, it is anticipated that a ring mass comparable to Mimas (the post-Voyager consensus; Esposito et al. 1984) can be detected to a few percent accuracy. A primordial ring compatible with current estimates of mass flux would need to be 5–10 times more massive and would be easily detected. Until the time that these fundamental measurements can be made, the question of the ring exposure age to pollution will not be resolved.

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Appendix 15: The Zero-Phase Opposition Effect

An entirely separate subset of scattering theory must be considered for very small phase angles (less than a degree or so), characterized by very strong brightening with the approach of true opposition. This so-called ‘opposition effect’ was initially interpreted in terms of shadow hiding in the regolith surface, and porosities were derived from the strength and width of the opposition surge. Early measurements of the opposition effect in Saturn’s rings were obtained by Franklin and Cook (1965) and Lumme and Irvine (1976). Lumme et al. (1983) concluded that the opposition effect resulted from shadow hiding (SH) amongst different ring particles in a classical many-particle-thick layer (Irvine 1966) with a very low volume filling factor. This was at odds with dynamical studies (Brahic 1977, Goldreich and Tremaine 1978) indicating that the rings should be only a few particles thick, as shown by N-body dynamical simulations (Salo 1987, 1992; Wisdom and Tremaine 1988, Richardson 1994, Salo et al. 2004, Karjalainen and Salo 2004; see Chapters 13 and 14). A partial resolution to the apparent contradiction between the photometric observations and the simulations was work by Salo and Karjalainen (2003), who used Monte Carlo ray tracing studies in dense particle layers. Interparticle shadowing can even produce a narrow, sharp opposition brightening for broad particle size distributions (French et al. 2007, Salo et al. 2008 DPS).

In addition however, SH within the regolith of an individual ring particle can contribute to the opposition brightening (Hapke 1986) and coherent backscattering (CB), or the constructive interference of incoming and outgoing light rays (Muinonen et al. 1991; Mishchenko and Dlugach 1992; Hapke 1990; Mishchenko 1993), can also contribute. Both SH in regoliths and CB are complicated functions of the surface structure of the particles and the optical properties of the grains, and have been the subjects of extensive theoretical and laboratory studies (Nelson et al. 2000, Nelson et al. 2002, Hapke et al. 2005, 2009).

It is a challenge to separate individual-particle scattering behavior (either SH or CB) from collective SH effects. In January 2005, Saturn’s rings were observed from the earth at true opposition. French et al. (2007) used HST’s WFPC2 to measure the sharp brightening of the rings with the approach of zero phase. Combined with the previous decade of HST observations at each opposition (Poulet et al. 2002), the WFPC2 data represent a uniform set of photometrically precise, multiwavelength measurements of the opposition effect of Saturn’s rings at ring opening angles from $|B| = 6–26^\circ$ and phase angles from $\alpha = 0–6^\circ$. Figure 15.41 (Fig. 4 of French et al. 2007) shows the opposition phase curve of the A ring from HST observations. Note the very strong, roughly two-fold increase in $I/F$ at small phase angles, most noticeable at short wavelengths. For comparison, the mutual-particle SH opposition effect is plotted for a range of assumed particle size distributions. At left, the dashed curves show the mutual-particle opposition effect for a monodispersion of 5 m radius particles. The solid lines show the narrower, more intense opposition surge resulting from a broader size distribution. At right, several even broader size distributions are assumed, but none of them exceed an amplitude of 1.5, compared to the observed surge of a factor of two.

Clearly, the narrow core of the opposition surge cannot be explained by interparticle shadowing alone. French
et al. (2007) fitted the opposition measurements to the composite model of Hapke (2002), which incorporates a wavelength-dependent CB component based on the theoretical predictions of Akkermans et al. (1988) and an explicit representation of SH by a particulate surface. The fits imply that the porosities of the ring particle regoliths are very high, ranging from 93% to 99%, and that the width of the narrow CB surge actually decreases with wavelength, rather than increasing. However, current CB models are somewhat idealized, and thus far, agreement between theory and experiments has been imperfect (Shepard and Helfenstein 2007, Hapke et al. 2009).

Regional variations in the opposition effect: The opposition effect in Saturn’s rings shows strong regional variability. French et al. (2007) fitted a simple linear-exponential model to the opposition effect, and Fig. 15.42 shows the variations in the fitted amplitude and half-width with ring radius; qualitatively similar results were obtained by Poulet et al. (2003) regarding radial variation, but with different ‘scale lengths’ inferred.

It seems likely that most of these variations are attributable to differences in the degree of interparticle shadowing and to the relative widths of particle size distributions, rather than to strong regional variations in the intrinsic particle or regolith scattering properties. In the C ring, the detailed variations correlate strongly with the optical depth variations, which affects the amount of interparticle shadowing. The opposition effect changes markedly at the boundary between the outer C and inner B ring, while (as shown in Section 15.4.5), the particle albedo and color, and thus presumably regolith properties, do not. Over the

![Fig. 15.41 Comparison of the observed A ring phase curves (crosses) to the mutual shadowing opposition effect calculated by photometric Monte Carlo simulations (curves). Dynamical simulations with seven different particle size distributions were conducted, ranging from q = 3 power laws for 0.05–5 m radius, to simulations with identical 5 m particles, (shown by different line types). At left, the two extreme size distribution models are compared to observations at different wavelengths. The single scattering albedos for the models, indicated in the middle panel, are chosen to fit the observed I/F at α ~ 6°. At right, the observations and single-scattering models are normalized to α = 6.35°. Also shown is the contribution from the adopted power-law phase function alone, (lowest dashed line) amounting to about 1.1 for the interval α = 0° to 6.35°. The color code refers to the wavelength of the observation, as shown in the center panel.](image-url)
Fig. 15.42 Radial variations in the amplitude, width, and slope of the opposition surge from linear-exponential model fits to HST WFPC2 observations of Saturn’s rings at five wavelengths, taken during Cycles 10–13. The colors are the same as in Fig. 15.41. The amplitude of the opposition effect (top) is nearly independent of wavelength except for the F336W filter (violet line), especially in the A and B rings, where the amplitude increases sharply at short wavelengths. (The gap in the F336W profiles between 107,000–118,000 km results from saturation of a unique low phase angle image, making the model fits unreliable in this region for this filter.) The width of the opposition surge varies strongly with ring region at short wavelengths in the A and B rings, and shows strong correlations with optical depth in the inner and outer C ring. The normalized slope (third panel) is most shallow for the optically thick central B ring. A radial profile of ring brightness is shown in the fourth panel, taken near true opposition ($\theta = 0.0043^\circ$ on January 14, 2005). The bottom panel shows the Voyager PPS optical depth profile, truncated at optical depth $D = 2$ because of limited signal to noise at high optical depths.
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