Scattering properties of Saturn's rings in the far ultraviolet from Cassini UVIS spectra

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Abstract

We use Cassini UVIS data to determine the scattering properties of Saturn’s ring particles in the FUV. We have replaced the scattering function from the classical Chandrasekhar single scattering radiative transfer equation for reflectance with a ring wake model for the A and B rings derived from stellar occultations. The free parameters in this model are the ring particle Bond albedo, \( A_B \), and the ring particle asymmetry parameter, \( g \), which equals the cosine of the most probable scattering angle of a photon from a ring particle. The spectrum of Saturn’s rings from 140 to 190 nm shows an absorption feature due to water ice shortward of 165 nm. We compare our model values for \( I/F \) to lit-side data at 155 nm and at 180 nm for regions in both the A and B rings. We used the unmodified Chandrasekhar model for the C ring and Cassini Division, and in all cases we determined \( A_B \) and \( g \) in the FUV for the first time. Values of \( A_B \) vary between 0.04 and 0.091 at 180 nm and between 0.012 and 0.019 at 155 nm. The variations across the ring of \( A_B \) at 180 nm is consistent with a greater abundance of non-ice contaminant in the C ring and Cassini Division and a minimum in contaminant abundance in the outer B ring. There is little variation in \( A_B \) at 155 nm across the rings, which suggests that the reflectance of the water ice and non-water ice material shortward of the 165 nm absorption edge are about the same. Values of \( g \) vary between ~0.68 and ~0.78 at 180 nm and between ~0.63 and ~0.77 at 155 nm showing that the ring particles are highly backscattering in the FUV. We find that the wavelength of the absorption feature varies with ring region and viewing geometry indicating a different photon mean path length, \( L \), through the outer layer of the ring particle (Bradley, E.T., Colwell, J.E., Esposito, L.W., Cuzzi, J.N., Toellerud, H., Chambers, L. [2010], Icarus 206 (2), 458–466). We compared \( I/F \) from 152 to 185 nm to a radiative transfer spectral model developed by Shkuratov et al. (Shkuratov, Y., Starukhina, L., Hoffmann, H., Arnold, G. [1999], Icarus 137, 235–246) and modified by Poulet et al. (Poulet, F., Cuzzi, J.N., Cruikshank, D.P., Roush, T., Dalle Ore, C.M. [2002]. Icarus 160, 313–324). We find that \( L \) is positively correlated with phase angle, which we attribute to multiple scattering within the particle on length scales comparable to \( L \). We extrapolate \( L \) to zero phase angle and find values of \( L \) at zero phase ranging from ~2 to 3 \( \mu \)m. This provides a direct measure of the distance from the surface of a ring particle to the first scattering center. \( L \) at zero phase is roughly constant across the rings suggesting the outermost 1.25 \( \mu \)m of the ring particles have the same structural properties in all ring regions. We azimuthally binned and interpolated observations of the unlit side of the A ring taken during Saturn orbit insertion to a 100 km resolution radial profile. We see halos (enhanced brightness) surrounding the Janus 4:3 and Janus 5:4 density waves. We also computed \( I/F \) across the A ring using the SOI observational geometry along with \( A_B \) and the power-law index, \( n \), derived from the retrieval approach from lit side observations. \( I/F \) determined by this technique agrees with results from the lit side analysis for the A2 ring but diverge for the inner and outer A ring, which we attribute to multiple scattering effects.

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1. Introduction

The Cassini Ultraviolet Imaging Spectrograph (UVIS) has obtained spectra of Saturn’s rings at a range of viewing and illumination angles over the course of the Cassini nominal and equinox missions. These data provide the first spatially resolved information on the spectral and photometric properties of Saturn’s rings in the far ultraviolet (FUV). FUV reflectance spectra of Saturn’s main rings contain an absorption feature shortward of 165 nm that is characteristic of water ice, first observed in Saturn’s rings in 12 IUE observations from 1982 to 1985 (Wagener and Caldwell, 1985).
Analysis of the brightness of the rings longward or shortward of the absorption edge provides information on the ring particle Bond albedo, $A_B$, and the ring particle phase function. The angular distribution of photons scattered from the ring particles is characterized by the asymmetry parameter, $g$, which is the cosine of the average scattering angle of photons from a particle (Henyey and Greenstein, 1941). In addition, the spectral location of the absorption feature provides information on the mean distance that a photon travels within a ring particle before exiting, which we quantitatively describe by the photon mean path length, $L$. $A_B$ is the fraction of incident photons scattered from a body back into space. Each of the constituents that comprises a ring particle has its own reflectance properties making $A_B$ dependent on the relative abundance and composition of the constituents. Epstein et al. (1984) estimated the fractional abundance of water ice in the rings to be greater than $90\%$ from microwave observations with the remaining few percent comprised of a contaminant that is primordial and/or due to meteoroid bombardment (Cuzzi and Estrada, 1998). Constraining $A_B$ is crucial to identifying the composition of the non-water ice material comprising the particle. The abundance of non-water ice material throughout the rings helps to constrain evolution models. Results from Elliott and Esposito (2011) suggest that darker rings are either less massive or exposed longer to meteoric bombardment, and probably both for the C ring.

Outer Solar System icy bodies have been shown to have a negative value of $g$, implying backscattering behavior (Verbiscer et al., 1990). This is in contrast to terrestrial water ice, which typically exhibits forward scattering behavior. According to Verbiscer et al., this is possibly due to more complex internal textures of outer Solar System ices due to low-temperatures and low-gravity conditions. Values of $L$ in the FUV spectral regime have already been shown to be less than $10\mu m$ (Bradley et al., 2010). Longer and shorter wavelengths may probe to deeper and more shallow depths, respectively, simply because shorter wavelengths in order not to be absorbed must be reflected from a shorter distance within the ice grains. These turn out to be the photons that are observed by the instrument.

$A_B$ and $g$ have been determined for visible and infrared spectral regimes by other researchers. Porco et al. (2005) showed $A_B$ for a broad range of radial distances covering the main rings at discrete wavelength intervals from 338 to 862 nm. For all ring regions $A_B$ decreased with decreasing wavelength with minimum values of 0.2–0.4 at 338 nm. Porco et al. (2005) used a Monte Carlo ray tracing model incorporating self-gravity wakes to model images obtained by the Cassini Imaging Science System (ISS). For the C ring and outer A ring they found $A_B = 0.32$ and $A_B = 0.63$, respectively. Using a power-law phase function, Porco et al. obtained power-law indices equal to 2.624 and 3.092 for the outer A and C rings, respectively. The power-law phase function formulation presented in Dones et al. (1993) describes the relation between the power-law index, $n$, and the asymmetry parameter, $g$ and has the following form:

$$P = C_n (\pi - 2g)^n$$

$$g = -\frac{1}{2} \int_0^{\pi} P(\alpha) \cos \alpha \sin \alpha d\alpha$$

where $\alpha$ is the phase angle, $C_n$ is a normalization constant, $n$ is the power-law index, and $g$ is the asymmetry parameter. Specifying $n$ uniquely defines the asymmetry parameter, $g$. Using this approach the values of $n$ obtained by Porco et al. translate to $g$ values of $-0.5$ and $-0.59$ for the A and C rings, respectively.

Retrieval of $A_B$ and $g$ requires that the scattering properties of the rings be understood and modeled correctly. For instance, since $L$ is a measure of the amount of ice a photon travels through, then multiply-scattered light will have a larger value of $L$ than singly-scattered light. The degree of scattering depends on the viewing geometry and is not an intrinsic property of individual ring particles. The geometry of a particular observation, i.e., the solar elevation angle ($B_s$), observer elevation angle ($B$), and phase angle ($\alpha$), affects the observed brightness and must be accounted for before the absolute value of $A_B$ can be retrieved. The effect that the observational geometry and scattering behavior have on the brightness of an atmosphere or body is characteristic of any atmosphere or surface where an instrument measures solar radiation scattered by the body. Radiative transfer equations that account for these effects have been derived for both classical atmospheres (Chandrasekhar, 1960) and surface reflectance models for bodies such as the Moon or icy satellites where the atmosphere, if any, is negligible (Hapke, 1981, 1993; Shkuratov et al., 1999). Saturn’s rings do not typically behave like a classical atmosphere or a solid surface, making it difficult to interpret the absolute values of the reflectance. This is caused in part by the self-gravity wake structure of the A and B rings (Colwell et al., 2006, 2007; Hedman et al., 2007) as well as by volume filling fractions greater than zero (a classical atmosphere) but less than one (a solid surface that is extremely tightly packed). Even the use of a radiative transfer code that is suitable for an optically thick atmosphere e.g., doubling adding, where multiple scattering is carefully modeled, is inappropriate for application to the rings since the volume filling factor is not negligible.

To retrieve $A_B$ and $g$ we have employed a single scattering analytical technique for dealing with the scattering properties of the rings that is based on a self-gravity wake model derived from stellar occultation data (Colwell et al., 2006, 2007). Because the self-gravity wakes are non-axisymmetric, the optical depth of the rings to incoming sunlight is not necessarily the same as the optical depth for the emerging rays observed by Cassini, even after taking into account the incidence and elevation angles. Therefore we use a modified Chandrasekhar model with the two optical depths treated independently. We assume, as did Cuzzi and Estrada (1998), that a ring particle is a centimeter to meter-sized object that is covered by a regolith of icy grains. Esposito (1979) showed that mutual shadowing between ring particles has only a small effect on multiply scattered photons. Furthermore, Cuzzi et al. (1984) argued that in the backscattering, low ring tilt angle geometry occurring during Voyager observations, $I/F$ is well approximated by neglecting multiple scattering. Since this analysis deals with backscattered light with relatively low ring tilt angle, with the exception of Saturn orbit insertion data presented in Section 4, we neglect multiple scattering between ring particles; however multiple scattering between regolith ice grains covering a ring particle must not be neglected. Below we refer to multiple scattered light as light that is scattered within the regolith of a ring particle and not to scattering between ring particles. Present within the regolith are non-ice contaminants that are intermixed with the ice grain although we do not make an attempt to retrieve the composition or abundance of the non-ice component. The classical Chandrasekhar model for singly-scattered light reflected from the rings is given by:

$$I = A_B \ast P \ast \frac{\mu_B}{4(\mu + \mu_B)} [1 - \exp(-\tau_B/\mu) \exp(-\tau_B/\mu_B)]$$

where $A_B$ is the ring particle Bond albedo, $P$ is the ring particle phase function, $\mu$ and $\mu_B$ are the cosines of the emission and incidence angles, respectively, and $\tau_B$ is the normal optical depth. $A_B$ is the number of photons that exit the ring particle divided by the number of incident photons that interact with the ring particle. This implies that both singly and multiply-scattered photons may contribute to the total number of photons that exit the particle. The problem with using this model for the rings is that the rings contain wake effects...
structure (for the A and B rings) and non-zero volume filling, rendering the problem different than for a classical atmosphere. Specifically, the optical depth terms, which describe the scattering behavior of the medium, relate the photon scattering to the normal optical depth. While scattering from the isolated particles within the gaps between wakes could be modeled in this manner, the wakes are opaque structures with a preferential orientation. Thus light scattering from a region of the rings that encompasses both wakes and gaps presents a complex problem of light scattering.

We replace the optical depth terms in the classical Chandrasekhar equation with terms derived from the granola-bar self-gravity wake model of stellar occultation data by Colwell et al. (2006, 2007). The reasoning behind this is as follows: the optical depth terms in the classical equation account for attenuation of photons due to atmospheric species, which may be considered to have a zero volume filling factor and are uniformly distributed. The normal optical depth, \( \tau_n \), is the absorption coefficient multiplied by unit length. Due to the presence of self-gravity wakes in the A and B rings, a simple relation between optical depth and an absorption coefficient is not possible. However, stellar occultation experiments directly measure the optical depth of the rings at different radial distances. These optical depths depend on the width, \( W \), separation, \( S \), and height, \( H \), of the self-gravity wakes, the optical depth of the inter-wake gaps, \( \tau_{gap} \), as well as the azimuthal angle relative to the wakes (\( \phi - \phi_{wake} \)) and line-of-sight angle to the ring plane (\( \beta \)). The simple “granola bar” model of Colwell et al. (2006, 2007) successfully explains the variation of optical depth with \( B \) and \( \phi \) so that optical depths at arbitrary viewing geometries can be calculated. The transparency of the rings in terms of the wake parameters is given by (Colwell et al. (2007)):

\[
T = \exp(-\tau_n/\mu) = \frac{S/W - H/W \sin(\phi - \phi_{wake}) \cot B}{S/W + 1} \exp(-\tau_{gap}/\mu) \tag{3}
\]

\[
T_o = \exp(-\tau_0/\mu) = \frac{S/W - H/W \sin(\phi_0 - \phi_{wake}) \cot B_0}{S/W + 1} \exp(-\tau_{gap}/\mu_0) \tag{3}
\]

In the C ring and Cassini Division the observed normal optical depth is insensitive to viewing geometry, and we use the unmodified Chandrasekhar model in those regions. The exponentials in Eq. (2) represent the transmission of the incoming solar flux and the outgoing scattered flux. For a homogeneous atmosphere these are each described simply by the normal optical depth of the atmosphere and a single angle specifying the slant path through the atmosphere. For rings with self-gravity wakes, however, there are additional geometric factors that determine the transmission. We use Colwell et al. (2007) ... to get Eq. (3). Then putting this in Eq. (2) we have the following modified Chandrasekhar granola bar model for \( I/F \):

\[
I = A_0 + P \cdot \frac{\mu_0}{4(\mu + \mu_1)} \left[ \frac{S/W - H/W \sin(\phi - \phi_{wake}) \cot B}{S/W + 1} \exp(-\tau_{gap}/\mu) \right] \times \left[ \frac{S/W - H/W \sin(\phi_0 - \phi_{wake}) \cot B_0}{S/W + 1} \exp(-\tau_{gap}/\mu_0) \right] \tag{4}
\]

with \( P \) given by Eq. (1).

2. Observations

A complete description of the UVIS instrument is given by Esposito et al. (2004). The observations processed in Section 3 were selected for their high signal-to-noise and spatial resolution (less than 4000 km per pixel) and are all taken from the sunlit side of the rings between 2005 and 2009 with a range of \( B_o \) from \( 3^\circ \) to \( 22^\circ \). In this investigation we have selected regions from each of the A, B, and C rings as well as the Cassini Division. The selection was based on regions with relatively little variation in normal optical depth throughout the radial extent of the region. Table 1 shows the lower and upper ring plane radii of the regions, and Table 2 lists the observations used in this investigation along with coverage and relevant geometrical information. Regions investigated in this analysis begin with the C4 region. The inner three regions of the C ring (C1–C3) are not discussed here due to large amounts of off-axis light and Saturn-shine in the signal. Similarly, data from
the inner Cassini Division are contaminated by light from the outer B ring.

Data reduction consists of the same technique described in detail in Bradley et al. (2010) and summarized here. We subtract the background counts from the raw count rate and calculate the radiance \( I \) in kilo-Rayleighs using an instrument calibration factor. Last we compute \( I/F \) by using the solar continuum flux \( pF \) from the SOLSTICE instrument on board the SORCE spacecraft (Sparn et al., 2005) that has been corrected for the rotation of the Sun to correspond to the face of the Sun towards Saturn at the time of the observation. We resample the UVIS data to the bandpass of SORCE SOLSTICE II (see Esposito et al., 2004; McClintock et al., 2005 for discussion on the spectral bandpass of each instrument), divide by \( \pi \) to get the radiance of a Lambertian surface and then divide this into the radiance, producing \( I/F \).

Uneven sampling in both the radial and azimuthal directions requires data to be azimuthally binned and then resampled to an evenly distributed one-dimensional radial array. We bin the data azimuthally over 30° increments to insure that the observer azimuthal angle does not vary greatly for a set of data points. Resampling the data to an evenly distributed array also insures that the average data over a radial bin is not weighted towards one particular sub-region within the bin due to larger numbers of pixels occurring within that sub-region. After this the evenly distributed grid of data points were averaged across each of the regions for this investigation.

Fig. 1 shows \( I/F \) versus phase angle for the C4, B3, CD2, and A3 ring regions and is color-coded according to \( B_0 \), which varies from \( \sim 1° \) to \( 22° \). Variations in \( I/F \) are dominated by changes in phase angle where \( I/F \) is inversely correlated to phase angle. A less dominant effect is the positive correlation of \( I/F \) with \( B' \). Dependency on \( B \) was checked and found to be negligible. Variations in \( I/F \) with \( \phi \) and \( \phi_{\text{wake}} \) may be significant due to non-axisymmetric self-gravity wakes as discussed in Section 1. We attach error bars to the data points, which we calculate by taking the inverse of the square root of the total raw counts at each data point. Assuming Poisson statistics this gives the fractional uncertainty, \( \sigma \). We then multiply \( \sigma \) determined at each data point by the value of \( I/F \) at each data point resulting in the fractional uncertainty of \( I/F \).

3. Results

Results are broken into two broad categories. The first is the retrieval of \( A_H \) and \( g \) by comparison of the Chandrasekhar-granola bar model to discretely averaged values of \( I/F \). We averaged \( I/F \) from 152 to 158 nm and from 175 to 185 nm and compared the averages to the model. The second is the retrieval of \( L \) by comparison of the Shkuratov et al. (1999) spectral model to \( I/F \) from 152 to 185 nm. This step must come second since the retrieved values of \( g \) from the comparison of the \( I/F \) to the Chandrasekhar-granola bar model are used as input to the Shkuratov model. We scaled the magnitude of the Shkuratov model to the value of \( I/F \) above and below the absorption edge. We chose the value of \( L \) that resulted in the best fit of the model to the data as the retrieved value of \( L \).
The free parameters within the Chandrasekhar-granola bar model given by Eq. (4) are $A_B$ and the power-law index, $n$, which is converted to the ring particle asymmetry parameter, $g$, through Eq. (1). We computed $I/F$ for each data point within a ring region for a specified value of $A_B$ and $n$. We varied $A_B$ between 0.005 and 0.4 in 0.005 increments and $n$ between 0.25 and 20 in increments of 0.25, which corresponds to $g$ values from $0.07$ to $0.95$. Values outside of the above limits consistently result in worse fits of the model to the data. Best-fit values of $A_B$ and $g$ were found by minimizing $D$ where

$$D = \frac{1}{N} \sum_{i=1}^{N} (m_i - d_i)^2.$$  

(5)

$N$ is the number of data points within a ring region, $d_i$ is the measured $I/F$ of measurement $i$, and $m_i$ is the model value of $I/F$.

3.1. Retrieval of $A_B$ and $g$

The eight panels of Fig. 2 show $I/F$ at 155 nm and 180 nm versus phase angle for the four B ring regions. Phase angles for observations used in the analysis of the B ring varied between $\sim 5^\circ$ and $75^\circ$. The variation with $b_0$ is clearly present in all regions of the B ring for both the short and long wavelength spectral regimes. The eight panels of Fig. 3 show $I/F$ and model results for the four A ring regions. For the A ring the phase angles for available observations used in this analysis varied between $\sim 5^\circ$ and $60^\circ$. Brightness dependency on $b_0$ is not as prevalent in the A ring as for the B ring. The four panels of Fig. 4 show $I/F$ and model results for the C4 and for the CD2 regions. The observations available for the Cassini Division spanned the least phase angle coverage in this analysis from $\sim 5^\circ$ to $40^\circ$ while those from the C ring varied between $\sim 5^\circ$ and $70^\circ$. The brightness dependency on $b_0$ that is seen in the B and A rings is minimal in both the C ring and Cassini Division.

Fig. 5 shows contours of $D$ corresponding to four regions in the rings. For consistency, values of the inner contour for each panel...
were chosen to be twice the minimum value of D for that region, which offered a reasonable visual estimate of the uncertainties in the determination of $A_B$ and $g$ across all regions of the rings and for the two wavelengths investigated. The broader minima of the D contours show that the model fit is less constrained for the short wavelength reflectance than it is for the long wavelength reflectance. We attribute this to lower signal levels at the short wavelengths leading to increased uncertainty in the measured $I/F$. For all rings regions the contours show a closed contour around a unique solution of $A_B$ and $g$ with smaller uncertainty at 180 nm than for 155 nm.

Figs. 6 and 7 show the retrieved values of $A_B$ and $g$, respectively, versus ring plane radius. At 180 nm $A_B$ peaks at 0.091 in the B3 region, remaining nearly the same for the B2 and B4 regions. The A ring regions as well as the B1 region have $A_B = 0.06 - 0.08$ while the C4 and Cassini Division regions have the darkest particles with $A_B$ between 0.04 and 0.05. At 155 nm $A_B$ has less variation across the rings with values between 0.012 and 0.019. This suggests that at 180 nm $A_B$ is sensitive to variations in the non-water ice fractional abundance. However, the relatively smaller variation of $A_B$ ratios at 155 nm suggests that at wavelengths below the absorption feature the reflectance of water ice and non-water ice components of a ring particle are comparable. Based on the quality of fit shown by the chi-square analysis displayed in Fig. 5, we can estimate the typical errors of determination of the parameters $A_B$ of ±20% and $g$ of ±30%, from the extent of the first contour around the best fit. These values are consistently larger than the errors associated purely with counting statistics, and give an empirical estimate of the quality of our retrievals.

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Fig. 7 shows the $g$ values the rings to be highly backscattering across the rings in the FUV spectral regime with values that vary between −0.68 to −0.78 for 180 nm and from −0.63 to −0.77 at 155 nm. For the 180 nm values the C ring and Cassini Division values are the lowest, which could possibly be related to non-water ice material in those regions; however there is not enough of a correlation between $g$ and $A_B$ in other regions of the rings to argue for
a relation between g values and non-water ice abundance. The 180 nm A ring g values increase with radius, which is consistent with the analysis that Dones et al. (1993) found from analyzing Voyager visible wavelength images.

3.2. Comparison of A$_B$ to other data sets

We compared A$_B$ from the A, B, C rings and Cassini Division to values from longer wavelength investigations. Fig. 8 is a composite that includes four A$_B$ values retrieved in this investigation along with A$_B$ near the same ring plane radii presented in Porco et al., 2005. The data points from Porco et al. are at wavelengths of 338 nm, 451 nm, 568 nm, 650 nm, and 862 nm. A$_B$ for this investigation extend the spectral coverage into the FUV to wavelengths of 155 nm and 180 nm. The Porco et al. data from different rings regions show considerable spread at the longest wavelengths and converge towards similar values as the wavelength decreases. The FUV data points appear to support this trend with A$_B$ all of the ring’s regions converging to values from ~0.01 to 0.02 at 155 nm.

3.3. Retrieval of L

Fig. 9 shows I/F spectra taken from the B3 region at four different phase angles. The water ice absorption feature near 165 nm shows a shift in the absorption edge to longer wavelengths for larger phase angle. Typically a spectral shift in the absorption edge is coincident with a change in L, where an increase in L results in the absorption edge shifting towards longer wavelengths. This is because photons traveling further in ice experience more absorption, thus decreasing the value of I/F at longer wavelengths.

We fit a spectral albedo model (Shkuratov et al., 1999) to I/F from 152 to 185 nm in order to retrieve L as a function of phase angle. L is the only free parameter in the Shkuratov model; however Poulet et al. (2002) modified the Shkuratov model to also allow for the ring particle asymmetry parameter, g, to be a free parameter. This modified version of the Shkuratov model was used with retrieved g values from the previous section to infer the value of L. We used water ice optical constants from Warren (1984) and Warren and Brandt (2008). The technique involved scaling the Shkuratov model in magnitude to the average of I/F at wavelengths above and below the absorption edge from each observation and fitting the model to the data over a range of L values from 0.1 to 10 μm in 0.1 μm increments. Initially a much larger range of L values were used, however it was found that values of L outside of 0.1–10 μm resulted in progressively worse fits. The selected value of L was found from taking the value of L corresponding to the minimum value of D given by Eq. (4) where for this case m and q are the spectral components of the scaled Shkuratov model and I/F, respectively, from 152 to 185 nm. An example of the best fit for the Shkuratov model to I/F from the B3 region is shown in Fig. 10.

The values of L were found as a function of phase angle for the same data points as those shown in Figs. 2–4. Results, shown in Fig. 11, indicate that there is a small upward slope in L with increasing phase angle that is attributed to multiple scattering effects. A linear fit was made to the values of L versus phase angle to quantify the y intercept, L$_0$, and the slope. In all cases the slope was positive to within one sigma uncertainty in the fit consistent with the assumption that L is positively correlated with phase angle due to increased multiple scattering effects. It follows that L$_0$, which predicts L at opposition, is a measure of twice the single scattering photon mean path length to the nearest scattering centers to the surface. L$_0$ across the rings show very little variation (Fig. 12) with values from ~2 to 3 μm.

4. Analysis of SOI data

On July 1, 2004 Cassini entered orbit around Saturn. Here we present a new analysis of the SOI (Spacecraft Orbit Insertion) data (Esposito et al., 2005) consistent with the new calibration, flat-fielding and parameter-retrieval techniques used for lit-face data in this paper and in Bradley et al. (2010). SOI data were taken over a 30 min segment of the orbit insertion phase where the spacecraft flew within 18,000 km of the unlit side of the rings and at a phase angle of 59.3°. The instantaneous size of a spatial pixel projected onto the ring plane was ~45 km per side; however the motion of the spacecraft throughout the integration period resulted in a skewed spatial pixel ~220 km in the radial direction. We apply the filtering and interpolation technique described in Bradley et al. (2010) to the data in order to azimuthally bin and create a one dimensional evenly distributed radial profile of I/F for the A ring. Fig. 13 shows the results for a 100 km interpolated radial...
profile of $I/F$. The data (solid line) show slight increases in brightness in the surrounding regions of the Janus 4:3, Janus 5:4, and Mimas 5:3 density waves with decreases in $I/F$ right at the density wave due to the increased optical depth and decreased transmission through the rings at those locations. The dotted line is an optical depth profile from a UVIS stellar occultation of $\alpha$ Arae that shows the increase in optical depth at these density waves. The regions of increased brightness extend a few hundred kilometers from the density wave, which is consistent with halos of greater brightness at 1.08 $\mu$m reported by Nicholson et al. (2008) in the simultaneous and co-aligned infrared SOI observation by the Visual and Infrared Mapping Spectrometer (VIMS).

We used $A_B$ and $n$ retrieved for the four regions in the A ring from Section 3 in the model for single-scattered transmission to determine $I/F$ for the geometry corresponding to the SOI observations. SOI observations were at a finer spatial resolution that the four regions determined for the lit side analysis so within each region we used the high resolution geometry from the SOI observations. The equation for single-scattered transmission is given by:

$$\frac{I}{F} = A_B \times P \times \frac{\mu_n}{4(M - \mu_n)} \left[ \exp\left(-\tau_n/H\right) - \exp\left(-\tau_n/\mu_n\right) \right]$$

where we used the self-gravity wake expressions for ring transmission (Eq. (3)) in place of the exponential terms. Fig. 14 shows the model $I/F$, which is $I/F$ from Eq. (6) for the SOI geometry using the self-gravity wake parameters determined from stellar occultations, compared to $I/F$ determined from the actual data from SOI observations. $I/F$ determined from data and the model agrees well for the A2 region; however, the model $I/F$ determined for regions A1, A3, and A4 are consistently lower than the data, especially for the A4 region. We expect an increase in $I/F$ for the outer A ring based on Voyager observations of the lit side analyzed by Dones et al. (1993). We tried replacing the power-law phase function with a double lobed Henyey–Greenstein phase function to investigate the possibility of forward scattering ring particles. However since this was used in a single scattering model and the phase angle is $\sim 60^\circ$ this did not result in better agreement between the model and data.
There are several possible explanations for this discrepancy including multiple scattering effects, scattering from the edges of self-gravity wakes, and three dimensional effects of self-gravity wakes that is not captured in the model. We discuss this in more detail in Section 5.

5. Discussion and conclusions

Following the arguments of Cuzzi et al. (1984) we assumed a single scattering model between ring particles to retrieve $A_B$ and $g$. It is possible that there could be a small contribution from multiple scattering between ring particles that we did not include. This implies that our retrieved values of $A_B$ and $g$ are unique only to the extent that single scattering is valid. Retrieved values of $A_B$ longward of the water ice absorption edge show a peak in the central and outer B ring and a minimum in the C ring and Cassini Division. $A_B$ throughout the A ring are similar to the B1 region. We interpret this as a measure of the relative abundance of the non-water ice material in the ring particles where the fraction is inversely correlated with $A_B$. The comparison of $A_B$ retrieved from this investigation to the values reported by Porco et al. (2005) shows that $A_B$ converges to similar values across the rings below the FUV absorption edge. We conclude that the reflectance of water ice and non-water ice materials are comparable below the absorption edge (at least to our low absolute precision at these low reflectances), thus the fractional abundance of the water ice and non-water ice materials are indistinguishable in the short wavelength regime. Also, since others have shown the rings to be mostly water ice (Cuzzi et al., 2009, 2010) and the long wavelength $A_B$ of Porco et al. (2005) for the B3 region is $\sim 0.85$, then we conclude that the non-water ice material must be very dark (comparable to water ice) at shorter wavelengths.

Lit side observational analysis by Dones et al. (1993) found that the single scattering albedo of ring particles remains relatively constant across the A ring with the exception of the trans-Keeler regime where the particle single scattering albedo increases by
We do not see an increase in $A_B$ from the lit side analysis of Section 3.1 for the outer A ring; however the A4 region extends from just outside the Encke gap to the ring edge so we do not resolve the trans-Keeler region for the analysis of Section 3.1.

Fig. 8 shows that $A_B$ drops significantly below 300 nm and is attributed to non-water ice material. Spectral modeling of $A_B$ from 300–4050 nm by Poulet and Cuzzi (2002) suggests that the ring particle surface is consistent with 93% water ice and 7% carbonaceous material. The carbonaceous material is thought to be primordial and/or due to meteoroid bombardment (Cuzzi and Estrada, 1998). Alternatively, Hendrix et al. (2010) have shown that NH$_3$ and a small amount of tholin fit the far ultraviolet to visible wave-length spectra (up to 1000 nm) from Enceladus; although this analysis does not cover the absorption features above 1000 nm. However, ultraviolet to mid-infrared laboratory measurements (350–15,500 nm) of water ice samples contaminated with organic compounds (Clark et al., 2009) as well as modeling using optical constants of organics and iron based constituents (Clark et al., 2012) have not been able to discriminate between the relative abundance of organics, iron, tholins, and other material responsible

\[ \sim 20\% \]

The shift in the spectral location of the absorption edge is shows an obvious trend with phase angle. Since $L$ is related to the spectral location of the absorption feature this merited an investigation of $L$ with phase angle using the Shkuratov model.

Fig. 9. $I/F$ from the B3 region at four different phase angles. The data are normalized to the $I/F$ at a phase angle of 34°. The shift in the spectral location of the absorption edge is shows an obvious trend with phase angle. Since $L$ is related to the spectral location of the absorption feature this merited an investigation of $L$ with phase angle using the Shkuratov model.

For an increase in the photon mean path length the absorption edge shifts towards longer wavelengths. As the photons travel further in ice they experience more absorption leading to a decrease in the value of $I/F$ at longer wavelengths.
for the non-water ice spectral features present in spectra of Saturn’s rings and icy moons. One hypothesis for the steep decrease in reflectance below 550 nm measured by VIMS (Filacchione et al., 2012) is that small amounts (parts per thousand) of nano-phase iron (less than 0.2 μm grain size) may be responsible for Rayleigh absorption in this spectral regime (Clark et al., 2012), although laboratory spectra have not been obtained to validate this. Modeling efforts by Clark et al. (2012) using Cassini VIMS data from observations of dark material on Iapetus suggests nano-phase iron and hematite to explain some unusual spectral features. This does not rule out the possibility of larger abundances of tholins and carbonaceous material, which is cosmochemically more likely, comprising the non-icy material as long as iron and hematite remain spectrally dominant. New laboratory spectra are required to determine whether or not icy mixtures containing nano-phase iron and hematite are spectrally dominant in the FUV.

There is little variation of g values across the rings indicating no radial dependence on the scattering properties of ice grains. The lowest values of g occur in the C ring and Cassini Division, which could possibly be related to the higher fractional abundance of

![Graphs showing retrieved L values in microns from comparing the Shkuratov–Poulet model to I/F. The value of g was fixed to the average of the short and long wavelength retrieved values of g resulting from comparing the granola bar model to I/F. A linear fit to the values of L (solid line) shows a positive slope with the value and one sigma uncertainty shown in the upper left corner. The slope still remains positive within the lower limit of the one sigma uncertainty.]

Fig. 11.
non-water ice material. However there seems to be no relation between \( g \) and \( A_B \) for the other regions so we conclude that the scattering asymmetry is insensitive to variations in ring composition. This may argue in favor of the morphological features of the ring particles and ice grain regolith dominating the scattering asymmetry. As pointed out by Verbiscer et al. (1990) the very cold temperatures at which outer Solar System ices exist could lead to the formation of complex structures during an event where the ice is melted and then freezes rapidly. Baragiola (2003) points out that cracks in ice induced by stresses are the main reason for low-temperature ices to be strongly backscattering.

The \( g \) values across the A ring increase slightly from the A1 to A4 region, implying that the outer A ring is less backscattering. This is consistent with results from Dones et al. (1993), who attribute this to either collisional packing of the ring particles or that the rings are physically thicker in the outer A ring than the rest of the A ring.

The ring \( I/F \) spectra shown in Fig. 9 shows that the absorption edge shifts to longer wavelengths as the phase angle increases. Comparison of \( I/F \) with the Shkuratov model showed \( L \) to be positively correlated with phase angle for all of the regions investigated. Under the assumption that the ring particle regolith is backward scattering, low phase angles result in mostly single scattered photons received by the instrument. At larger phase angles, there is an increase in the multiple scattered contribution to the signal. Consequently the multiple scattered photons travel a greater total distance within ice leading to an increase in the value of \( L \). Since \( L \) is larger for multiple scattered photons, the result is that the absorption edge shifts towards longer wavelengths.

The extrapolated value of \( L \) at zero phase, \( L_0 \), may be thought of as the single scattering photon mean path length. Physically this means that \( L_0 \) is twice the average distance the photon travels into an ice grain before being backscattered. The small variation of \( L_0 \) with ring plane radius despite large variations in (long wavelength)
$A_n$ across the rings suggests that the FUV photons are sampling scattering centers that are all about the same distance from the surface. Scattering may occur because of contaminants located within the ice matrix, a crack within the grain, or because the photons travel completely across a grain and scatter off the other side. $L$ may not necessarily reflect the size of the ice grains since scattering may occur at some point inside the grain. Typical $L$ values of $\sim 3 \ \mu m$ translate to $\sim 1.5 \ \mu m$ from the surface to the scattering center and the wavelengths we are dealing with are $0.165 \ \mu m$. Nicholson et al. (2008, Fig. 4) report a best fit to the A and B ring using a grain size of about $10 \ \mu m$ from analysis of data from the Visual Infrared Mapping Spectrograph (VIMS) on Cassini. Alternatively Filacchione et al. (2012) retrieve grain sizes that are somewhat larger than $10 \ \mu m$, which may be the result of different modeling approaches. Nevertheless grain sizes determined from VIMS spectra results in a mean path length (or grain size) $\sim 10$ times that retrieved from the FUV data, while their wavelength regime is about 10 times longer than UVIS. Thus it may be that both instruments are merely sampling to a depth governed by the wavelengths of the observed photons. This implies that the ice grains do not contain significantly large scattering centers in the outer few microns since the long wavelength investigations of VIMS show a larger photon path length; therefore photons in the FUV are probing the extreme surface layers of the grain.

Halos have been detected by others (Nicholson et al., 2008; Dones et al., 1993). According to Nicholson et al. halos appear as regions of increased brightness in reflected light for phase angles below 30° and as minima at phase angles from 50 to 70°. Nicholson et al. who were reporting on SOI observations (unlit side transmitted light at 59° phase) made by VIMS corresponding to the same SOI data presented here, saw increased regions of brightness surrounding strong resonances, consistent with our results. Esposito et al. (2005) suggested density waves released brighter material from the particles with the bits diffusing away from the sources in the density wave region. This is caused by streamline crowding (Lewis and Stewart, 2005), which damps the interparticle velocity and allows temporary clumps to grow. These clumps lead to an increase in the velocity of smaller particles surrounding these clumps, which then impact the clumps and excavate purer ice (see the predator–prey model of Esposito et al., 2012).

The single scattering transmission model that made use of $A_n$ and $n$ from the lit side analysis of Section 3 compared well with the SOI $I/F$ from the A2 region but over-predicted $I/F$ for the other regions of the A Ring. Since the single scattering reflectance model fit the data quite well in the lit side analysis of Section 3 we conclude that multiple scattering is negligible for the lit side analysis therefore the values of $A_n$ and $g$ derived in Section 3 should be reasonably accurate. The cause of the poor model fit to the unlit side SOI data for the A1, A3, and A4 regions may be a combination of different effects. One is that multiple scattering contributions may be more significant in transmission for the A1, A3, and A4 regions, which our single scattering model shown in Eq. (5) does not account for. Salo and Karjalainen (2003) performed Monte-Carlo radiative transfer simulations and showed that multiple scattering is typically a greater fraction of the total transmitted light than for reflected light. The average of gap optical depths for the A1–A4 regions determined by UVIS occultation measurements are 0.128, 0.095, 0.131, and 0.181, respectively. Nicholson et al. (2008) suggested that all the light seen on the unlit side observations must be scattered by particles in the gaps between the self-gravity wakes because the wakes themselves are opaque. The gap optical depth in A2 is smaller than elsewhere in the A ring, so the contribution from multiple scattering should be smallest in this region. However as the gap optical depth increases by $\sim$ a factor of 2 in the A4 region the single scattering model of Eq. (5) underestimates $I/F$ as the contribution from multiple scattering grows. The discrepancies between the single-scattering “classical-granola bar” model and the SOI data in Fig. 14 are qualitatively consistent with this explanation of a correlation between the multiple-scattered contribution and the optical depth of the gaps between the self-gravity wakes.

A second explanation deals with the morphology of self-gravity wakes. The wakes should be three-dimensional structures resembling long flattened, ellipsoids (Meinke et al., 2012). At the moderate phase angles of SOI, the light will diffuse between these structures, and the scattered light is more like diffuse reflection from the edge regions. The self-gravity wake margins will appear to UVIS FUV like the “silver lining” of clouds on Earth. Those parts of the rings viewed from the dark side will light up if they have the
right geometry and optical thickness, which may be the case for the geometry of the SOI observations.

A third explanation deals with the optical depth of the single scattering model we are using. The Chandrasekhar-granola bar model has only two optical depth values and misses the three-dimensional nature of the rings, which may be more prominent in the outer A ring, or in the regions of overstability. These geometrical effects and the fact that the Toomre critical length may be smaller in the outer A ring due to the lower surface mass density might have a larger effect on the results than multiple scattering.

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References


