Mimas’ far-UV albedo: Spatial variations

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1. Introduction

Mimas is the innermost of Saturn’s classical medium-sized moons. It is 397 km in diameter and orbits at 3.08 Saturn radii (R_S). Voyager images of Mimas revealed an old, heavily cratered surface, dominated by the large Herschel crater near the leading hemisphere equator (Smith et al., 1981). Its surface composition, based on visible-near-infrared (VNIR) data, is dominated by H_2O ice (Cruikshank et al., 1998, 2005). It has a high visible albedo (geometric albedo ~1.0, Verbiscer et al., 2007) and a flat spectrum in the visible (Buratti, 1984) consistent with H_2O ice.

Using Voyager data, Buratti et al. (1990) found that Mimas may be somewhat brighter and redder (based on the orange–green/violet ratio, 550–580 nm/410 nm) on the trailing hemisphere (centered on 270°W) than on the leading hemisphere (centered on 90°W); this was attributed to E-ring particle accretion. Enceladus and its south polar plume are the source of the broad E-ring (Porco et al., 2006; Spahn et al., 2006), within which Mimas orbits. Dynamical modeling of the E-ring grains (Hamilton and Burns, 1994) showed that, due to the orbital eccentricities of the grains, those at the orbit of Mimas (inside the 3.95 R_S orbit of Enceladus) overtake Mimas in its orbit and are expected to bombard or coat the trailing hemisphere, while at Tethys and the other satellites exterior to Enceladus, the E-ring grains impact primarily the satellite leading hemispheres.

Prior to Cassini, Mimas had not been studied deep in the UV. The Voyager UV filter was centered on 350 nm. The ultraviolet is an important wavelength regime for studying the effects of space weathering processes, because primarily the uppermost layers of the regolith and grains are sensed. Here we present far-ultraviolet (FUV) results from observations of Mimas by the Cassini Ultraviolet Imaging Spectrograph (UVIS). The results are compared with visible wavelength images from Cassini ISS and thermal data from Cassini CIRS.
2. Data sets and analysis

The Cassini UVIS (Esposito et al., 2004) uses two-dimensional CODACON detectors to provide simultaneous spectral and one-dimensional spatial images; the second spatial dimension is acquired by slewing the UVIS slit across the target body. The far-UV channel of UVIS covers the 111.5–191.2 nm range. The detector format is 1024 spectral pixels by 64 spatial pixels. Each spectral pixel is 0.25 mrad and each spatial pixel is 1 mrad projected on the sky; the low-resolution slit used for the observations discussed here has a spectral resolution of 0.48 nm and spatial IFOV of 1.5 mrad in the spectral dimension. Here we discuss four observations, which took place during two Cassini orbits, described in Table 1. Three of the observations were mosaics, where the UVIS slit was placed at distinct locations on the surface. The fourth observation (126MI_ICYLON003) consisted of three slews across the body to make an image. Each of these slews lasted approximately 26 min and the entire observation was 80 min; the integration time was 120 s. The observational geometry is shown in Fig. 1. In this analysis, we focus on 126MI_ICYLON003, as it provides the most complete coverage, and compare with the other three observations, which are used primarily for photometric analysis. We average the three swaths of 126MI_ICYLON003, and also examine the first swath only, when the spatial resolution was highest.

We analyze the data in terms of the reflectance, which is given as \( r = I/F; I \) is the measured signal from Mimas and \( nF \) is the incident solar flux. The measured signal is dependent not only on the albedo of Mimas but also on the photometric properties of the surface, as discussed further in the next section. We used solar data measured by SOLSTICE on the SOFIA spacecraft (McClintock et al., 2000), scaled to Mimas’ heliocentric distance on the days of the observations, with the proper time difference to get the correct solar longitude; any temporal variations in solar flux on these timescales and at these wavelengths are negligible.

The FUV spectra of the icy saturnian moons all show the strong signature of water ice, an absorption edge near 165 nm (e.g., Hendrix and Hansen, 2008; Hendrix et al., 2010). As a result, the spectra of Mimas and the other moons are generally bright longward of 165 nm and dark shortward of 165 nm; in this analysis we focus on the longer-wavelength end of the H2O absorption. In Fig. 2 we show the \( I/F \) measured during the observations at wavelengths 170–190 nm. The data have been calibrated and RTG background subtracted. In these images, the data are “smoothed” in that the image accounts for smear within each pixel due to motion of the body during the observation. Fig. 2 also shows a representation of Mimas at the mid-time of each observation, to display the viewing and lighting geometry. We note that, in the FUV data, there is no indication of the giant Herschel crater, consistent with the idea that UVIS senses the uppermost layers of the surface. Since Herschel is a relatively old feature, this emphasizes that the effects discussed below are young.

3. Photometric correction

We wish to remove the variations in signal that derive from photometry, in order to determine the normal albedo of Mimas’ surface. To estimate the UV photometric characteristics of Mimas, we follow the methods of Buratti et al. (e.g., Buratti and Veverka, 1983; Buratti, 1984, 1985; Buratti et al., 1990). A simple form of a photometric function that has been used with many Solar System surfaces is

\[
I/F = Af(x)\mu_0/(\mu + \mu_0) + (1 - A)\mu_0
\]

where \( A \) represents the fraction of light that is singly scattered (dependent on the albedo) and \( f(x) \) represents the combined effects of mutual scattering among the particles, macroscopic roughness and the single-particle phase function; \( x \) is the phase angle. The terms \( \mu \) and \( \mu_0 \) are the cosines of the emission and incidence angles, respectively. For \( A = 1 \), all light is singly-scattered. The first term of Eq. (1) represents “lunar-like” scattering, where limb-darkening is not significant and single scattering dominates. The second term in Eq. (1) represents Lambert scattering.

In Fig. 3, we display data from scans along the photometric equator (\( \omega \)) (after e.g. Buratti, 1984) for each of the four Mimas observations. The photometric equator is defined as the line intersecting the sub-solar and sub-observer points on the surface. For each of these scans, we have solved for the best-fit values of \( f(x) \) and \( A \) in the photometric model of Eq. (1). We find good fits to the scans for 126MI_ICYLON001 and 126MI_ICYLON002 using this model, demonstrating that the surface can be represented using a constant \( A \) value and thus relatively little albedo variation at this resolution. However, the same model applied to 126MI_ICYLON003 does not provide a very close fit, and this is interpreted as being due to FUV albedo variations across the surface observed in this observation. Toward the anti-saturnian hemisphere (positive sin(\( \omega \)) values in Fig. 3c for this observational geometry), the

Fig. 1. Observational geometry for 126MI_ICYLON003. In this observation, the UVIS slit was oriented as shown; the slit was scanned three times across the body. The UVIS spatial pixels are indicated by the small white boxes; the green lines designate right ascension and declination. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)
surface is brighter (higher albedo) than predicted, and toward the leading hemisphere (negative \( \sin(\omega) \) values in Fig. 3c), the surface is darker (lower albedo) than predicted. Similarly, the model fits the 012MI_ICYLON008 scan adequately toward the trailing hemisphere (positive \( \sin(\omega) \) values in Fig. 3d for this observational geometry) but the surface is brighter than predicted toward the anti-saturnian hemisphere (negative \( \sin(\omega) \) values in Fig. 3d). We use the best-fit photometric model for 126MI_ICYLON003 to correct the observation for the photometric behavior of the surface and study the resultant normal albedo.

4. Results

The far-UV normal albedo pattern of Mimas is shown in Fig. 4 for the 126MI_ICYLON003 observation; the normal albedo was derived by dividing the measured data by the photometric correction as described in Section 3. An albedo variation across the surface is evident. A bright region, which appears to be centered near the apex of the anti-saturnian hemisphere (~180°W), extends from ~20°S to the north pole, and wraps over the north pole onto the high latitudes of the leading hemisphere; the surface becomes progressively darker toward the apex of the leading hemisphere, and the bright region is ~3 times brighter than the darkest region. The bright region in the north is not mirrored in the southern hemisphere, on the observed anti-saturnian region, resulting in a latitudinal asymmetry in albedo. To study this a bit further, we show (Fig. 5) scans within two latitude bands plotted against geographic longitude. Both scans show a dramatic (non-photometric) dropoff in brightness toward the leading hemisphere. The southern hemisphere scan is lower in brightness overall than the northern hemisphere scan. This is not expected to be due to photometric characteristics of the regolith, as both the sub-solar point and the sub-spacecraft point are near the equator. Thus, the overall FUV albedo pattern differs from that measured at visible wavelengths (Schenk et al., 2011) or thermal wavelengths (Howett et al., 2011), and it does not follow the “lens” shape of the longer wavelengths; this is discussed further in Section 6.

The reflectance spectra of the FUV-bright region and the FUV-dark region are shown in Fig. 6. Both spectra show the water ice absorption edge near 165 nm (e.g. Hendrix et al., 2010); because water ice is so bright longward of 165 nm, the difference between the spectra suggests that the UV-bright region is richer in water ice than the UV-dark region; the UV-dark region has more absorbing non-ice species and/or is less scattering than the UV-bright region.

5. Exogenic processes at Mimas

There are many weathering processes that act on the satellite surfaces in the saturnian system, including bombardment by photons, charged and neutral particles, and ice grains as shown in the diagram of Fig. 7. To aid in the interpretation of the UVIS results, we discuss each of these processes and their expected results.
Fig. 3. Scans along the photometric equator. The photometric equator is the line defined by the sub-solar and the sub-spacecraft points. Negative values are toward the terminator, positive values are toward the sunlit limb. Data are fit with the model of Eq. (1) (red line): (a) 126MI.ICYLON001; (b) 126MI.ICYLON002; (c) 126MI.ICYLON003; (d) 012MI.ICYLON008. Good fits are obtained especially for 126MI.ICYLON001 and 126MI.ICYLON002; the fit is not so good for 126MI.ICYLON003 and this is interpreted as due to albedo variations across the surface. The same albedo variation may contribute to the data-model mismatch toward the terminator in 012MI.ICYLON008.

Fig. 4. Mimas UV (170–190 nm) normal albedo images. There is more than a factor of 3 variation in albedo across the anti-saturnian hemisphere. (a) 126MI.ICYLON003 swath 1; (b) 126MI.ICYLON003 average; (c) 012MI.ICYLON008. The high albedo may not persist across the entire trailing hemisphere, but does not seem to get as low as on the leading hemisphere. Longitude lines are shown in 30° increments.
As mentioned previously, E-ring grains preferentially impact the trailing hemisphere of Mimas (Hamilton and Burns, 1994). The exact accretion pattern of these grains is not completely known, but their speeds are different enough that we expect a broad bombarding distribution onto the surface of Mimas. The solution for their orbits depends on factors such as their initial rate of speed and charging history. Since simulations of E-ring grain orbital inclinations (Horanyi et al., 2008) show that they can grow quite large (e.g., 15°), the latitudinal extent (vertical profile) of the E ring is much greater than Mimas’ radius. Therefore, we expect that there are grain trajectories that at least reach the polar regions of Mimas. A schematic diagram of the estimated pattern of E-ring grain accretion on Mimas is shown in Fig. 8a.

5.2. Cold plasma

An additional exogenic process on the trailing hemisphere is bombardment by the corotating cold plasma. The expected bombarding pattern is a “bulls-eye” shape on the trailing hemisphere but we cannot comment extensively on any potential UV effects based on the lack of trailing hemisphere coverage in the UVIS dataset to date. However, the central part of the trailing hemisphere could be slightly darker than the high latitudes and anti-saturnian region (Fig. 4c), possibly an effect of plasma darkening of that region. Schenk et al. (2011) note a weak IR/NUV bright region in Cassini images of the Mimas trailing hemisphere, which was suggested could be due to cold plasma bombardment. The expected pattern of bombardment of cold plasma is shown in Fig. 8b. We also expect any nanograin, whose motion would be close to that of the plasma ions, to bombard the trailing hemisphere in a similar manner.

5.3. High-energy electrons

In contrast to the plasma and low-energy (below ~1 MeV) electrons discussed above, electrons with energies above ~1 MeV, because of their retrograde drifts in the dipole field of Saturn, preferentially bombard the leading hemisphere of Mimas (Schenk et al., 2011; Paranicas et al., 2011). This interaction results in the “lens” feature seen in ISS data (Schenk et al., 2011) as well as the thermal anomaly seen in CIRS data (Howett et al., 2011).

We note that there is enhanced darkening (in the IR/NUV ratio image, or blueing in the color image), presumably due to enhanced weathering, in the Saturnward and anti-Saturnward portions of Mimas’ leading hemisphere lens (Schenk et al., 2011). A direct comparison between the ISS ratio image and a UVIS image is shown in Fig. 9, where the ISS ratio image (Fig. 9a) is projected at the same perspective and resolution as the UVIS image of Fig. 4a. The dark “ansa” of the lens is obvious in the ISS data at this resolution (though the color contrast is quite low compared to the UVIS image); the surface here is relatively bright at 340 nm. Thus, the ISS ratio image displays a distinct variation in IR/UV3 brightness across the lens (at the level of ~10%), with the ansae being darkest (or bluest). The UVIS image (Fig. 9b) hints at an “ansa” near 150°W (a relatively dark region nearly surrounded by brighter terrain) (this only appears in the 126ML_ICYLON003 swath 1 image of Figs. 4a and 9b); however, whereas the IR/NUV ratio stays relatively constant in value between ~90 and 140°W, the far-UV albedo grows darker with decreasing longitude in this region. It is worth noting that near-UV wavelengths sense deeper into the surface than far-UV wavelengths, and therefore it seems sensible that the lens (correlated mostly with cm depths) would be more apparent in the near-UV; this is discussed further in Section 6.3.

This enhanced darkening in the ISS IR/UV ratio at the ansae of the lens may be explained if we take into consideration additional components of energetic electron drifts near the moon. These components occur due to the electromagnetic field perturbations that should exist downstream of Mimas.

The main interaction mode in Mimas’s interaction with the magnetosphere is thought to be plasma absorption, as earlier studies indicate that Mimas cannot sustain a substantial sputter-produced atmosphere that may lead to a Europa or Io-type of magnetospheric interaction (Saur and Strobel, 2005). Plasma absorbing moons have their interaction region downstream with respect to the cold plasma corotation flow. The main feature of this interaction region is a plasma cavity (or wake) that forms due to absorption at the moon’s trailing hemisphere. Plasma is almost absent in the deep wake and refills within few moon radii downstream (Roussos et al., 2008). The near absence of cold plasma in the wake requires that magnetic pressure increase there. Since retrograde electrons are primarily guided by magnetic field gradients, any variations in the field can alter their trajectories. We believe the strengthening of B in the cold plasma wake leads to a small divergence from purely azimuthal trajectories. This is our hypothesis about why the ansae are more heavily weathered than the center of the lens. We expect to pursue this subject more formally in future work.
6. Interpretation of UVIS results considering the exogenic processes and effects

6.1. Spectral effects of E-ring grain accretion

The FUV spectral variation between the UV-dark region of the central leading hemisphere and the UV-bright region of the anti-saturnian hemisphere (Figs. 4 and 6) suggests more water ice in the UV-bright region. This is consistent with the idea of E-ring grains accreting on the surface in the bright region, which would be expected to deliver relatively pure water ice to the surface. The albedo variation suggests that E-ring grains reach high latitudes (at least in the north – the latitudinal asymmetry is discussed below). The interaction between the fine E-ring grains and the surface is expected to be dominant on the trailing hemisphere (Hamilton and Burns, 1994; Buratti et al., 1998), consistent with the westward brightening in ICYLON003 and the brighter trailing hemisphere in 012ML_ICYLON008 (Fig. 4).

One additional method of understanding the accretion of Saturn’s E-ring grains onto Mimas is to look for changes in particle sizes on its surface as measured by the Cassini Visual Infrared Mapping Spectrometer (VIMS). VIMS is an imaging spectrometer with 352 spectral channels between the wavelengths of 0.30–5.1 μm (Brown et al., 2004). The spectral region between 1 and 2.5 μm is particularly rich in the characteristic absorption bands of volatiles and minerals and is thus well-suited to identifying and mapping the composition of surfaces. In addition, the depths of the spectral bands of water ice near 1.05, 1.3, 1.52 and 2.0 μm are known to change as the particle size changes (Clark and Lucey, 1984). Because the E-ring is dominated by particles in the 0.1–1.0 μm (radius) size range (Kempf et al., 2008), an abundance of small particles would be consistent with an enhanced flux from the E-ring as discussed below.

Fig. 10a shows VIMS spectra extracted from three regions on Mimas: the northern rim of the large crater Herschel; the center of the leading side, and the center of the trailing side (each spectrum is averaged from 20 pixels). A band depth was calculated for the two deepest spectral lines, at 1.52 μm and 2.0 μm, by the following formula:

\[
\frac{(R_C - R_0)}{R_C}
\]

where \(R_C\) is the relative reflectance of the continuum and \(R_0\) is the relative reflectance at the center of the band position. The continuum was computed by fitting a straight line to it and computing the value of that line at the center of the band position. Fig. 10b shows these results for both bands plotted with the predictions of Clark and Lucey (1984). The band depths on the trailing side (10–50 μm in diameter) are substantially less than those on the leading side (20–80 μm in diameter) and imply smaller particles on average. Herschel has the largest grain sizes of any region of Mimas (50–100 μm). These results are consistent with a flux of smaller particles from the E-ring impacting the trailing hemisphere of Mimas.

The derived grain sizes of the surface of Mimas are substantially greater than the sizes of particles in the E-ring. Thus, there must be a process (perhaps annealing) that acts subsequently to, or during, the accretion of the particles, causing regolith grain growth.

6.2. Chemical effects: \(H_2O_2\) production

We suggest that the UV images also show compositional variations across the surface that are due to radiation- and photolysis-induced chemistry. In particular, hydrogen peroxide (\(H_2O_2\)) is readily produced both by radiolysis and photolysis of ice (e.g., Johnson and Quickenden, 1997; Cooper et al., 2003; Shi et al., 2011). Peroxide is known to absorb efficiently in the UV, even in small amounts (e.g., Carlson et al., 1999) and is thought to cause reddening in the UV on other icy satellites (e.g., Hendrix et al., 1999; Hendrix and Johnson, 2008).

Using the UV solar spectrum at Saturn’s heliocentric distance, and the high-energy electron and proton distributions at Mimas (Paranicas et al., 2011), we modeled the formation of \(H_2O_2\) in ice on the basis of laboratory measurements. Here we summarize the model and calculations, with a more detailed discussion to be given in a future publication.

We describe the time evolution of the \(H_2O_2\) molecule number density \(n\) in ice bombarded simultaneously by different particles at different energies as follows:

\[
\frac{dn}{dt} = n_w \sum_i \int \frac{d\phi_i}{dE} \sigma_{ciE} dE - n \sum_i \int \frac{d\phi_i}{dE} \sigma_{diE} dE
\]

where \(t\) denotes time, \(n_w\) the \(H_2O\) density, \(E\) the particle energy, \(\sigma_i\) and \(\sigma_d\) the \(H_2O_2\) creation and destruction cross sections, and \(d\phi_i/dE\) the energy distribution of the bombardment flux of species \(i\). Eq. (2) implicitly neglects cooperative effects between particles, i.e., involving (negligible) terms higher than first order in flux.

We surveyed the published laboratory ion, electron and UV photon data (Gerakines et al., 1996; Gomis et al., 2004a, 2004b; Hand and Carlson, 2011; Loefller et al., 2006; Moore and Hudson, 2000; Zheng et al., 2006) comparing steady-state concentration, column density, peroxide yields (per particle and eV), and creation and destruction cross sections against particle energy, range, and energy deposition per unit distance \(S = dE/dx\), where \(S\) is equivalent to (i) the stopping power for ions and electrons, and (ii) absorbance times energy for photons. We found \(\sigma_i\) to be proportional to \(S\):

\[
\sigma_{ciE} = aS_{ciE}
\]
Fig. 8. Simplified representations to demonstrate the relative importance and contributed effects to the UV albedo from different processes. (a) Assumed E-ring grain accretion pattern. We expect that E-ring grains impact Mimas globally but that there is a region on the leading hemisphere where lower overall abundances accumulate. Here we assume a uniform accretion by E-ring grains; we do not include any possible decrease in E-ring grain accretion away from the trailing hemisphere apex. (b) Cold plasma bombardment pattern. The plasma is expected to darken the surface but this darkening will compete with brightening by E-ring grain accretion. (c) High-energy electron bombardment pattern (after Paranicas et al., 2011), also showing the enhanced bombardment regions of the lens ansae discussed in Section 5.3. (d) Assumed photolysis pattern for the southern summer – equinox timeframe. (e) Model combining the different processes and assuming that the photolysis component dominates for latitudes southward of 30°S. We also do not include the high-energy electrons shown in (c) because we assume that those penetration depths are largely not seen by UVIS. The cold plasma is not included as its effects are not seen in the view as seen by UVIS. (f) Combination model shown at the same projection as the Mimas UVIS image of Fig. 4c, also shown here (g).
where \( a = 5.0 \pm 1.6 \times 10^{-18} \text{ cm}^2 \text{ eV}^{-1} \) Å based on laboratory data for \( S = 0.026-52 \text{ eV/A} \) measured in the temperature range 77–80 K (i.e., within the estimated Mimas daytime temperature range of \( \sim 40-95 \text{ K} \) (Howett et al., 2011)). The proportionality of \( S \) and \( \sigma_r \) implies a constant creation \( G \)-value of \( G_c = \frac{\sigma_r}{\sigma_{\text{int}}} \cdot \frac{E}{S} \cdot \frac{\text{mol}}{\text{cm}^2} \) implying a constant number of \( \sigma_{\text{int}} \) molecules created per unit of energy deposited is consistent between laboratory experiments, for different radiation types. A constant \( G_c \) implies \( \sigma_{\text{int}} \) formation directly from \( \text{OH} \) radicals following water dissociation (Loeffler et al., 2006) if one considers that the number of \( \text{H}_2\text{O} \) dissociation events is proportional to the deposited energy.

For ions and electrons we did not find any statistically significant trend in \( \sigma_d \) over the measured range of \( S \), with \( \sigma_d = 10^{-7} \text{ cm}^2 \). However for UV photons \( \sigma_d \) is limited by the optical absorption cross section, which is only \( \sim 8.7 \times 10^{-17} \text{ cm}^2 \) for Lyman-\( \alpha \) (121.6 nm) photons (Vatsa and Volpp, 2001) and decreases with wavelength (Sander et al., 2011) to \( \sim 1.6 \times 10^{-24} \text{ cm}^2 \) at 300 nm (Chu and Anastasio, 2005). Measured \( \text{H}_2\text{O}_2 \) UV photo-dissociation quantum yields are close to unity (Sander et al., 2011), and we therefore take \( \sigma_d \) as equal to the (wavelength-dependent) absorption cross section. This assumption yields good agreement with the average \( \sigma_d \) of \( \sim 1.5 \times 10^{-18} \text{ cm}^2 \) implied by measurements with a hydrogen microwave discharge light source (Gerakines et al., 1996) when one integrates the predicted \( \sigma_d \) over the lamp spectrum (Jenniskens et al., 1993).

The solution to Eq. (2) with constant flux is given in terms of \( \text{H}_2\text{O}_2 \) concentration \( C \) by:

\[
C = (C_0 - C_\infty) \exp(-t/\tau) + C_\infty
\]

where

\[
C_\infty = \left( a \sum_i \int \frac{d\phi_i}{dE} S_i dE \right) \tau,
\]

\[
\tau = \left( \sum_i \sigma_d \phi_i \right)^{-1}
\]

and \( C_0 \) and \( C_\infty \) denotes the initial and steady-state concentrations. A rigorous calculation would require estimates of \( C \) and the time constant \( \tau \) versus depth below the ice surface (considering the range of the different irradiation species), and estimates of the effect of the (depth-dependent) peroxide concentration on the reflectance spectrum, taking into account multiple reflections and scattering in an ice regolith (Hapke, 1981). However for simplicity we analyze here the concentration and time constant on the ice surface to get a rough idea of the concentrations and time scales.

We estimate an average Mimas surface \( \text{H}_2\text{O}_2 \) concentration from electrons and ions of only \( \sim 0.008\% \) on the leading hemisphere, whereas by contrast on the illuminated surfaces the UV...
photon flux and the production of H$_2$O$_2$ is calculated using Eqs. (2)–(6). The time constants are estimated using these equations, and the result is that the production of H$_2$O$_2$ is dominated by photons and the equilibrium is produced much higher peroxide concentrations, e.g., $C_\text{eq} \sim 0.13\%$ at 45° latitude (taking into account the average 23% solar insulation at this latitude at the time of the measurement). Considering that Carlson et al. (1999) show a strong absorption (a factor of $>4$ decrease in reflectance between 330 nm and 210 nm) with just 0.13% H$_2$O$_2$ in ice, it would appear to be plausible that hydrogen peroxide is causing the FUV-darkness on the leading-southern region of Mimas.

Using Eqs. (2)–(6), we calculate the time constants to be $\sim 8$ years for unilluminated surfaces on the leading hemisphere, and $\sim 65$ days on illuminated surfaces at 45° latitude. However, given that we have not accounted for several factors, we estimate the production timescale to be longer. For instance, the production and destruction rates, and steady-state concentration of H$_2$O$_2$ decrease with depth into the ice (i.e., at 170–190 nm, we are sampling a few microns into the surface – but the incoming photon flux decreases with depth over the top few tens of nanometers). Also, topographical shadowing has not been included, and would slow down H$_2$O$_2$ production. Furthermore, the production timescale will vary depending on subsolar point throughout the summer period. Thus, we estimate that the production timescale for H$_2$O$_2$ production is likely closer to $\sim 1$ year.

What these timescales imply is that the H$_2$O$_2$ buildup in the summer hemisphere ice occurs over about a year; once the surface moves into the fall-winter-spring period, the destruction of H$_2$O$_2$ begins to dominate, and occurs on the timescale of $\sim 8$ years. The UVIS results thus appear to be consistent with slow H$_2$O$_2$ destruction by electrons and ions in the shadowed northern latitudes during the $\sim 7$ year winter timeframe, followed by a several month recovery in peroxide during the transition to summer as surfaces are newly illuminated. Fig. 8d shows a schematic representation of the possible distribution of photolytically-produced peroxide for the observation timeframe.

6.3. Sampling and penetration depths

The fact that UVIS measures the leading hemisphere low latitudes of Mimas to be relatively dark is interesting, because this is also the area where ISS measurements show the surface to be relatively bright in the near-UV (340 nm) – the blue “lens” (Schenk et al., 2011) previously mentioned. This lens is relatively bright in the NUV (340 nm); the UVIS results, in the far-UV, suggest that the low latitudes of the leading hemisphere are relatively dark (along with the southern latitudes). We consider the idea that the UVIS, ISS and CIRS measurements are sensing different depths in the surface layer. Mimas and the other icy saturnian satellites exhibit a dramatic absorption at near-UV wavelengths ($\sim 200–350$ nm); they are very dark at FUV wavelengths (Hendrix et al., 2010) while being bright in the visible. There is thus a significant albedo change between the ISS UV filters and the UVIS data sets. This absorption is important in understanding the difference in albedo patterns. Estimating the wavelength-dependent optical constants for Mimas’ surface, the absorption path length near 180 nm is on the order of a few microns, while it is on the order of centimeters at 340 nm. Parancik et al. (2009) demonstrate that high-energy electrons or the secondary photons emitted as they slow down can deposit energy to a depth of about 1 m (1 MeV electrons have a penetration depth of 0.4 cm); thus the electrons produce damage and effects at deeper levels in the regolith than are sensed by UVIS. The uppermost layers of the regolith are doped on both hemispheres, but the leading hemisphere will also have the deeper penetration. Therefore, the CIRS-measured thermal anomaly exhibits a spatial morphology different from the UVIS–measured albedo. That is, CIRS is sensing the effect of the deeply-penetrating high-energy electrons while UVIS senses primarily the effects in the very topmost layers modified by the $\sim 1$-um E-ring grains and photolytic H$_2$O$_2$ production. The ISS images display effects at intermediate depths. Thus the model of Fig. 8e applies to the shallow sensing depths of FUV wavelengths only. At these FUV wavelengths, the high-energy electrons are not as important as E-ring grains and photolysis, the effects of which will overlay the mostly deeper electron effects. For UVIS–through CIRS-sensed depths, gardening by micrometeoroid and E-ring bombardment will affect the timescales of processing and have not been considered here; E-ring grain bombardment is less significant on the leading hemisphere of Mimas than on the trailing hemisphere (note #16 in Hamilton and Burns, 1994).

We note that we do not consider as a darkening agent any dark material that could be indigenous to Mimas. Though any such material may be brought to the surface via impact gardening, we assume here that other processes (e.g. photolysis, radiolysis) dominate at the depths sensed by UVIS. We have also not considered exogenic dark material, largely because it is not clear that this is an important process at Mimas (e.g. Clark et al., 2008) and also because the albedo pattern does not seem consistent with this type of source; exogenic dark material will certainly be considered in future analyses of UVIS data of Dione and Rhea. That being said, we note that, even in the “bright” regions on Mimas, the albedo is lower than the expected albedo of pure water ice (Hendrix et al., 2010), indicating that there is photolytic production of H$_2$O$_2$ (and/or darkening by cold plasma bombardment) in this region at Mimas subsequent to the accretion of the E-ring grains, and/or the E-ring grains are not pure H$_2$O ice, consistent with Cassini Cosmic Dust Analyzer measurements (Postberg et al., 2008), or perhaps some processes has occurred en route to Mimas.

7. Conclusions

Mimas exhibits a surprisingly interesting spatial variation in far-UVCUV (170–190 nm) albedo, as measured by Cassini UVIS, which appears to be the result of a combination of processes. The anti-saturnian hemisphere and north polar region are brighter than the leading hemisphere; this extends somewhat onto the trailing hemisphere though observations there are of lower resolution. This brightening is consistent with E-ring grain accretion which is also demonstrated in the VIMS dataset. On the trailing hemisphere a competing process is plasma bombardment which tends to darken the surface by enhancing absorption at these wavelengths; this competition may explain why the trailing hemisphere is not overwhelmingly brighter than the leading hemisphere; in fact the primary FUV bright region may actually be the anti-saturnian region discussed here and also likely on the not-observed sub-saturnian region – regions where the E-ring grain accretion occurs and the plasma bombardment is minimal (confined to a bulls-eye pattern on the trailing hemisphere).

We anticipate that photolysis produces H$_2$O$_2$ globally, but that this is particularly pronounced in the southern regions for this timeframe. We note that, even in the “bright” regions on Mimas, the albedo is lower than the expected albedo of pure water ice (Hendrix et al., 2010), indicating that there is photolytic production of H$_2$O$_2$ (and/or darkening by cold plasma bombardment) in this region at Mimas subsequent to the accretion of the E-ring grains, and/or the E-ring grains are not pure H$_2$O ice (this is perhaps the most likely explanation, given CDA measurements (Postberg et al., 2008)).

The latitudinal asymmetry in the UV albedo is proposed to be the result of accumulated H$_2$O$_2$ in the surface ice over the southern summer. We expect that Mimas observations later in the Cassini mission could reveal a darkening of the northern leading hemisphere as summer approaches that region and photolysis acts to produce H$_2$O$_2$ there, while the southern hemisphere darkening is...
gradually erased by plating out of fresh E-ring grains and the slow destruction of H2O2 by ions and electrons, in the relative absence of photons.

The lens-shaped feature that appears in the ISS ratio image (Schenk et al., 2011) and the CIRS image (Howett et al., 2011) is not obvious in the UVIS images; this is attributed to the different sampling depths in the instruments and the penetration depths by the different processes. The Mimas lens does not have a uniform ratio/color value across it: the ansae are distinctly darker in ISS color ratios (i.e., brighter at 340 nm), attributed to preferential bombardment of the sub- and anti-saturnian portions of the leading hemisphere by energetic electrons. A hint of the dark ansa on the anti-saturnian side is seen in the UVIS data—the region is relatively dark at 170–190 nm, likely due to enhanced production of H2O2 in that region.

The combined FUV effects detected on Mimas are indicators of radiolytic and photolytic weathering processes in the Saturn system and are expected to be present to varying degrees on the other icy saturnian moons; they will be investigated further in future studies.

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