Photolysis of H$_2$O–H$_2$O$_2$ mixtures: The destruction of H$_2$O$_2$

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A B S T R A C T

We present laboratory results on the loss of H$_2$O$_2$ in solid H$_2$O + H$_2$O$_2$ mixtures at temperatures between 21 and 145 K initiated by UV photolysis (193 nm). Using infrared spectroscopy and microbalance gravimetry, we measured the decrease of the 3.5 $\mu$m infrared absorption band during UV irradiation and obtained a photodestruction cross section that varies with temperature, being lowest at 70 K. We use our results, along with our previously measured H$_2$O$_2$ production rates via ionizing radiation and ion energy fluxes from the spacecraft to compare H$_2$O$_2$ creation and destruction at icy satellites by ions from their planetary magnetosphere and from solar UV photons. We conclude that, in many cases, H$_2$O$_2$ is not observed on icy satellite surfaces because the H$_2$O$_2$ photodestruction rate is much higher than the production rate via energetic particles, effectively keeping the H$_2$O$_2$ infrared signature at or below the noise level.

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1. Introduction

Surfaces of most icy bodies in the outer Solar System and interstellar space are constantly bombarded with energetic particles and photons. Radiolytic products from these impacts can be detected from Earth and spacecraft by comparison of features in their reflectance spectra with those obtained in the laboratory. Some of our more recent laboratory studies using radiolysis to simulate the space environment (Loeffler et al., 2006a,b; Raut et al., 2012) have been motivated by the detection of H$_2$O$_2$ on Europa (Carlson et al., 1999), the lack of or lower than expected abundance of NH$_3$ detected on the surface of many saturnian icy satellites, such as Enceladus (Brown et al., 2006; Verbiscer et al., 2006), and the higher than expected CO$_2$-CO ratio found in the interstellar medium (Whittet et al., 1998).

In the work we report here, we have investigated the stability of H$_2$O$_2$ mixed in H$_2$O–ice when it is photolyzed with longer wavelength UV photons (>180 nm), which are weakly absorbed by H$_2$O. Our previous work on H$_2$O$_2$ was initially motivated by the detection of the 3.5 $\mu$m absorption band on the surface of Europa by the Galileo Near-Infrared Mapping Spectrometer (NIMS) (Carlson et al., 1999; Hansen and McCord, 2008). More recent ground-based studies have confirmed the NIMS results and have shown that there is nearly an order of magnitude more H$_2$O$_2$ in Europa’s leading hemisphere than in its trailing hemisphere (Hand and Brown, 2013). The presence of H$_2$O$_2$ on Europa’s surface, predicted by Johnson and Quickenden (1997), is not too surprising given that this satellite is subject to a high radiation flux (Cooper et al., 2001) and is mostly composed of water ice, a combination of which has long ago been shown to lead to H$_2$O$_2$ production (Ghormley and Stewart, 1956). Soon after the discovery of H$_2$O$_2$ on Europa, multiple laboratories verified that under relevant experimental conditions H$_2$O$_2$ could indeed be formed via radiolysis of water ice (Moore and Hudson, 2000; Comis et al., 2004; Loeffler et al., 2006b; Zheng et al., 2006; Hand and Carlson, 2011). Unlike former studies, these radiolysis measurements were made in situ at the irradiation temperature studied, ensuring that the H$_2$O$_2$ detected was from irradiation and not from thermal reactions that may occur during warming. Although the amount estimated on Europa and in the laboratory was <1% with respect to H$_2$O, the strength and location of the absorption band made it seem likely that the NIMS detection on Europa would be the first of many on solid icy surfaces. However, new detections of condensed H$_2$O$_2$ on other surfaces have not been forthcoming, as the only other possible detection of H$_2$O$_2$ (Newman et al., 2007) on the icy satellite Enceladus has been disputed (Hodyss et al., 2009; Loeffler and Baragiola, 2009). Interestingly, Ganymede and Callisto, two other jovian satellites similar in composition and surface temperature to Europa but with lower radiation flux, have shown a slope in their ultraviolet reflectance spectra that is suggestive of H$_2$O$_2$ (Hendrix et al., 1999) yet no infrared absorption feature near 3.5 $\mu$m absorption region has been detected.

It is important to note that while Europa’s surface is the only one in outer space where condensed H$_2$O$_2$ has been unequivocally detected in situ (Loeffler et al., 2006a, 2006b; Zheng et al., 2006; Hand and Carlson, 2011), there are still other terrestrial environments where H$_2$O$_2$ may be present. For example, it has been detected in the stratosphere of Venus (Nieman et al., 2008) and in comets (Lamy et al., 2002) and in the presolar interstellar medium (Whittet et al., 1998).

It is important to understand the destruction of H$_2$O$_2$ on icy satellites in order to understand the implications for the presence of this important species on other icy worlds, such as Callisto, Proteus, and Tethys, which have been proposed as potential environments for life. The destruction of H$_2$O$_2$ on Europa is of particular interest because it is thought to be the source of the red material on the surface (Carlson et al., 1999) and because it may be a key component of the plumes from Enceladus (Fones et al., 2009). The destruction of H$_2$O$_2$ on Europa is also important for understanding the impact of solar UV photons on the surface composition of icy satellites, which may be relevant for the search for biologically relevant molecules on icy worlds.
detected, there have been a few gas phase detections of H₂O₂. For instance, H₂O₂ has been detected in Mars’ atmosphere using both submillimeter (Clancy et al., 2004) and infrared spectroscopy (Encrenaz et al., 2004). Interestingly, the abundance of H₂O₂ in the martian atmosphere appears to have a time dependence, as these values were three to six times higher than previous upper limits provided estimated infrared spectroscopy (Encrenaz et al., 2002). This temporal dependence is also supported by more recent measurements by the Herschel telescope, which has not been able to observe H₂O₂ up to the previous detected levels (Hartogh et al., 2010). Most recently, using submillimeter spectroscopy gas phase H₂O₂ has been detected in the interstellar medium (Bergman et al., 2011), where solid H₂O₂ has been predicted to exist (Tielens and Hagen, 1982) but has yet to be detected.

The paucity of definitive H₂O₂ detections in outer space, especially in the solid phase, contrasted with its relative ease to produce and detect in the laboratory, has led us to begin investigating possible mechanisms that could preferentially destroy H₂O₂ throughout the detection depth of the icy satellite surfaces (tens’s of microns for the 3.5 µm band). Recent laboratory studies show that one possibility for the absence of H₂O₂ on Ganymede, Callisto and the trailing hemisphere of Europa is that this molecule may be consumed by thermally-induced reactions with contaminants in the ice, such as SO₂ (Loeffler and Hudson, 2013). Another likely mechanism, which is likely active in both pure and contaminated ice, is that the hydrogen peroxide may be efficiently destroyed by longer wavelength UV photons (>180 nm), which are weakly absorbed by water (>2 cm absorption length, Warren and Brandt, 2008) and can thus penetrate deeply into the surface ice. To test this possibility, we have photolyzed low concentrations of H₂O₂ in solid H₂O mixtures with UV photons (193 nm) at temperatures between 21 and 145 K. During photolysis, we have measured the photodestruction of H₂O₂ by monitoring the decrease of the 3.5 µm band with infrared spectroscopy and the photodesorption of the sample by monitoring the mass loss of our sample with our quartz crystal microbalance. Finally, we have extrapolated our photodestruction results to estimate the timescale on which this mechanism would be active on multiple surfaces in outer space.

2. Experimental details

All experiments were performed inside a cryopumped stainless-steel vacuum chamber on a radiation-shielded cryostat (see Loeffler et al., 2006c). The base pressure of the chamber was ~3 × 10⁻¹⁰ Torr and 1–2 orders of magnitude lower inside the shield. Solid hydrogen peroxide–water films were vapor deposited at 110 K onto an optically flat gold mirror electrode of a 6-MHz quartz-crystal microbalance (QCM). The measured areal mass (mass/area) with infrared spectroscopy, and the photodesorption of the sample by monitoring the mass loss of our sample with our quartz crystal microbalance. Finally, we have extrapolated our photodestruction results to estimate the timescale on which this mechanism would be active on multiple surfaces in outer space.

Irradiation was performed at normal incidence using a GAM ArF excimer laser (193 nm; 10 ns pulse width). The laser beam was defocused using a MgF₂ lens (f = 50 cm) to cover a rectangular spot ~25 mm × 75 mm at the target, larger than the active diameter of the microbalance (6 mm) to avoid multi-photon excitations or heating during each laser pulse. To measure the photon fluence reaching the target, we replaced the QCM with an Ophir power meter, which measured constant beam intensity across the area of the QCM. In these experiments, we measured that the laser delivered pulses of 1.2 × 10¹⁵ photons/cm²/pulse uniformly across the films at a rate that we varied from 2 to 16 Hz during the experiment. The values of fluence are calculated taking into account the ~20% light reflected by the gold substrate (Canfield et al., 1964).

In addition to microbalance gravimetry, in situ characterization of our films was performed using infrared spectroscopy. The infrared specular reflectance between 1.5 and 15 µm was measured at an incident angle of 35° using a Thermo-Nicolet Nexus 670 Fourier Transform infrared spectrometer at 2-cm⁻¹ resolution. The spectra were divided by the reflectance of the gold mirror substrate taken before film deposition and converted into absorption by taking the natural logarithm.

To quantify the column density of hydrogen peroxide present in the sample, we have typically calculated the band area of the infrared absorption at 3.5 µm by subtracting a non-linear continuum from the spectrum in optical depth units (Loeffler et al., 2006b). However, as is seen in Fig. 1, the H₂O₂ absorption band is very weak at high fluxes, and thus here we analyze the derivative of the optical depth (ln reflectance) spectrum. The absorption feature is more pronounced in the derivative, which is likely active in both pure and contaminated ice, and converted to thickness if the mass density is known (Sack and Baragiola, 1993). The measured areal mass can be converted to film column density η (molecules/cm²) if the film composition is known, and converted to thickness if the mass density is known (Sack and Baragiola, 1993).

The H₂O–H₂O₂ mixtures were grown from a liquid solution of hydrogen peroxide and water using a glass doser (Loeffler and Baragiola, 2011). Each film contained between 0.5% and 2% H₂O₂, which was calculated from the band area of the infrared H₂O₂ absorption band at 3.5 µm, using previously calibrated band strengths at the same thickness (Loeffler et al., 2006b). After growth, samples were annealed to 135 K to allow diffusion to form the thermodynamically stable dihydrate diluted in water instead of clusters of hydrogen peroxide (Loeffler and Baragiola, 2005). After warming to 135 K, the samples were subsequently taken to the temperature where they were irradiated: 21–145 K.

Fig. 1. Infrared spectrum of an H₂O+H₂O₂ mixture photolyzed at 100 K with 193 nm photons. Spectra from top to bottom at 2850 cm⁻¹ is after 0, 1.6, 6.3, and 50 × 10¹⁰ photons/cm². The spectra have been offset vertically for clarity. The caption focuses in on the 3.5 µm absorption band of H₂O₂.

3. Results

Fig. 1 shows the infrared spectrum of our H₂O+H₂O₂ mixture before, during and after UV photolysis at 100 K between 3000 and
650 cm⁻¹. The spectra are dominated by the broad absorption bands of H₂O₂: 3ν₁ (2243 cm⁻¹), ν₂ (1621 cm⁻¹), and ν₁ (780 cm⁻¹) and a weaker absorption band for ν₂ absorption band (2860 cm⁻¹) of H₂O₂. Photolysis has no clear effect on the water absorption bands, as expected since the absorption coefficient of H₂O at the wavelength of our laser (193 nm) is 0.159 m⁻¹ (Warren and Brandt, 2008), and thus only ~0.0003% of light is absorbed by H₂O. Unlike water, the absorption band of H₂O₂ decreases during photolysis. However, no new absorption bands, such as those of HO₂ or HO₃, reported at 1142 cm⁻¹ and 1259 cm⁻¹ respectively (Cooper et al., 2006), are detected above the noise level in the spectra shown here or any of the other temperatures studied, which is likely due to the low level of H₂O₂ in the samples. Finally, we note that the general trends seen here were also observed when we photolyzed our sample with a broad band Hg lamp.

To quantify the photodestruction of H₂O₂, we analyzed the peak-to-peak of the derivative (2860 cm⁻¹) absorption band of H₂O₂ during photolysis. The normalized results for all the temperatures studied are shown in Fig. 3. In all cases, the H₂O₂ decreases with laser fluence and continues to decrease at the highest doses used in this experiment. Interestingly, the rate of H₂O₂ destruction appears to be highest at the lowest temperature, consistent with radiolysis studies on H₂O₂ + H₂O mixtures (Hudson and Moore, 2006) at 19 and 80 K. However, as the temperature is increased above 70 K, the destruction rate of H₂O₂ also increases. From Fig. 3, we can determine the fluence needed to destroy half of the H₂O₂ in the sample, F₁/₂, and have shown these values in Table 1. One can see from Table 1 that the range of calculated F₁/₂ varies significantly: the slowest decay (70 K) is ~9 times slower than at 21 K but only ~5 times lower at 145 K.

In addition to infrared spectroscopy, we also used our microbalance to estimate the photodesorption of our sample at T ≤ 130 K, where thermal sublimation of H₂O is negligible. Assuming the mass loss is entirely due to H₂O₂, we estimate the yield to be ~1–4 × 10⁻⁹ H₂O₂/phot. Comparing these values to F₁/₂ given in Table 1, we estimate that at most only about 3% of the H₂O₂ in the sample would be lost due to photodesorption by F₁/₂, suggesting that the decrease in the infrared band area observed (such as in Fig. 1) is due to photodesorption and not photodesorption. Thus, the lack of detected decomposition products in Fig. 1 is likely a combination of the initial low H₂O₂ concentration in the sample and the fact that the infrared signal from the main decomposition product, OH (see Section 4), is masked by the OH stretch absorption from the water matrix.

### 4. Discussion

That solar light decomposes hydrogen peroxide has been known for more than a century (Downes and Blunt, 1877). Most studies since have been done in liquid aqueous solutions or in the gas phase. The few studies of radiation effects in frozen aqueous solutions of H₂O₂ done at temperatures relevant to the outer Solar System, have focused on the analysis of the electron paramagnetic resonance spectra of OH and HO₂ radicals, e.g., Wyard et al. (1968), Harrison and Symons (1993), and Beine and Anastasio (2011). Several interesting experiments have been performed with H₂O₂ isolated in rare gas matrices (e.g., Khriachtchev et al. (2000)), but the absence of the hydrogen-bonded matrix would make questionable a translation of those results to our case. Rather, to explain our data, we will base the majority of our discussion on what has been learned from studies performed in the gas phase, keeping in mind the difference in solid vs. gas phase reactions, namely the higher probability of radical recombination due to the presence of a lattice.

#### 4.1. Photolysis pathways

First, we observe no apparent changes in H₂O infrared absorption bands during photolysis (Fig. 1) and note that H₂O is essentially transparent to the 193 nm light, we neglect the initial role of water and consider only photoabsorption by H₂O₂.
Photoabsorption at 193 nm occurs with a cross section (in cm$^2$ molecule$^{-1}$) of $\sigma_a = 6 \times 10^{-19}$ (vapor) and $1.26 \times 10^{-18}$ (liquid solution) (Lin et al., 1978) and leads to dissociation (Bersohn and Shapiro, 1986), which is confirmed by a total quantum yield for dissociation near unity (Vaghjiani et al., 1992). Photoabsorption promotes an oxygen lone pair to an anti-bonding orbital, leading to the scission of the weak (2.15 eV) O–O bond, with two ground-state and vibrationally unexcited hydroxyl fragments rotating in opposite sense around the O–O axis (Grunewald et al., 1986). Alternatively, the HO–OH bond may be broken, leading to a H atom and HO$_2$ (Gerlach-Meyer et al., 1987), as in (2) below:

\[ \text{hv} + \text{H}_2\text{O}_2 \rightarrow \text{OH} + \text{OH} + 4.3 \text{ eV (80\%)} \]

(1) \[ \text{hv} + \text{H}_2\text{O}_2 \rightarrow \text{HO}_2 + \text{H} + 2.5 \text{ eV (20\%)} \]

(2) The relative importance of each of these outcomes, and the absence of a significant O-atom product have been established by several later studies (Vaghjiani et al., 1992; Schiffman et al., 1993; Nakayama et al., 2005).

In the condensed state, the dissociation cross-section $\sigma$ is lower than the absorption cross-section $\sigma_a$ because of the cage effect. Dissociation products collide with the cage of molecules surrounding the excited molecule and can return to reform hydrogen peroxide by the exothermal reactions OH + OH $\rightarrow$ HO$_2$ and H + HO$_2$ $\rightarrow$ H$_2$O$_2$. As a result, the quantum yield $\Phi = \sigma/\sigma_a < 1$. This is likely the reason why $\Phi$ is seen to drop from 1.6 OH/photon in the gas phase to 0.7 OH/photon in the condensed phase (Chu and Anastasio, 2005).

As the fluence of photons increases, reaction products accumulate in the sample and secondary reactions can occur if the initial H$_2$O$_2$ concentration is sufficiently high and diffusion allows collisions involving radicals, which occurs at higher temperatures, more than about 100 K. In addition, the 193 nm photons can dissociate some products. The photoabsorption cross sections for gas phase HO$_2$ is $4 \times 10^{-18} \text{ cm}^2$ (Sander et al., 2006), or approximately seven times higher than gas phase H$_2$O$_2$, while photoabsorption by OH, OH, O, and H$_2$ are negligible compared to that of H$_2$O$_2$.

Of the main reaction products given in (1) and (2), only HO$_2$ could possibly be detected in our sample, as the OH is masked by the H$_2$O and the H atom will not have a detectable infrared signature. However, no HO$_2$ is observed in the infrared 1142 cm$^{-1}$ during any point in photolysis at all temperatures studied. Thus for the point of modeling our results, we assume that (1) is the dominant destruction pathway, and thus the only secondary reaction that may be important is the reformation of H$_2$O$_2$ via OH recombination. Thus, we write the dependence of the hydrogen peroxide concentration [H$_2$O$_2$] with time $t$ as:

\[ d[\text{H}_2\text{O}_2]/dt = -\phi \sigma [\text{H}_2\text{O}_2] + \phi \sigma [\text{H}_2\text{O}_2][k][\text{OH}] \]

(3) \[ dP/dt = -\sigma P + \sigma PCH \]

(4) Since two hydroxyls form every time hydrogen peroxide is destroyed, we can relate the two molecules by the following relation:

\[ P = H = 2[P_0 - P] \]

(5) where $P_0$ is the initial column density of hydrogen peroxide. We then can rewrite (5) in terms of only the hydrogen peroxide column density:

\[ dP/dF = -\sigma P + \sigma P2c[P_0 - P] = -\sigma P(1 - 2cP_0) - 2c\sigma P^2 \]

(6) We can integrate (11) to obtain:

\[ \frac{P}{P_0} = \frac{a}{(a + b)e^\sigma - b} \]

(7) \[ a = \sigma[1 - 2cP_0]; \quad b = 2c\sigma P_0 \]

(8)

Fig. 3 shows the least square fits of Eq. (7) to the experimental data. The closeness of the fit to the data supports our assumption that the primary decomposition product is OH and that H$_2$O$_2$ can be reformed by hydrogen recombination. The net destruction cross section measured at each temperature is shown in Fig. 4. It starts with an initial high value at 21 K and drops but begins to increase above ~100 K, at the onset of OH diffusion in ice (Kroh et al., 1962). Radical mobility allows for interaction of radicals and further hydrogen peroxide destruction by the Haber–Weiss chain reaction (Lunak and Sedlak, 1992):

\[ \text{OH} + \text{H}_2\text{O} \rightarrow \text{HO}_2 + \text{H}_2\text{O} \]

(9) \[ \text{HO}_2 + \text{H}_2\text{O}_2 \rightarrow \text{OH} + \text{H}_2\text{O} + \text{O}_2 \]

(10) which can be terminated by a number of reactions that destroy OH, such as

\[ 2\text{OH} \rightarrow \text{H}_2\text{O}_2 \]

(11) \[ 2\text{OH} \rightarrow \text{H}_2\text{O} + \text{O} \]

(12) The O atom produced in reaction (13) may be important for the production of other secondary products, such as O$_2$ or O$_3$, yet none of these are observed in our sample.

4.2. Astrophysical implications

To calculate the effect of solar irradiation on the jovian icy satellites we need to integrate the product of the solar flux and the destruction cross section along the wavelength spectrum. The solar flux at these satellites is obtained from the irradiance measured by the UARS probe outside the Earth’s atmosphere (Woods et al., 1996) on 29 March 1992 scaled out to the 5.2 AU distance of the
jovian system by dividing by the square of the distance. To arrive at the destruction cross section, we first calculate the photodestruction rate as the integral of the photon flux and the absorption cross section $\sigma_\alpha$, given by Lin et al. (1978) above 189 nm for aqueous solutions and by Suto and Lee (1983) for gaseous $\text{H}_2\text{O}_2$ below 193 nm; we multiplied the Suto and Lee data by a factor of two to match the aqueous solution data. Fig. 5 shows the solar flux at the jovian satellites, the photodestruction cross-section, and the differential absorption rate per nm. The integral of the latter curve gives an absorption rate of $7 \times 10^{-6} \text{ s}^{-1}$ at the subsolar point.

To obtain the photodestruction rate, the absorption rate needs to be multiplied by the quantum yield for dissociation, $\Phi$, which is less than 1 due to the cage effect. It is given by the ratio of our photodestruction cross section (Fig. 5) and the photodestruction cross section of $1.3 \times 10^{-15} \text{ cm}^2$ at 193 nm (Lin et al., 1978). For an average equatorial temperature of 106 K appropriate to Europa (Spencer et al., 1999), $\Phi \sim 0.1$. Assuming that $\Phi$ does not vary much with wavelength, as happens for room temperature solutions between 205 and 400 nm (Goldstein et al., 2007), the initial (zero fluence) photodestruction rate at Europa at the subsolar point is $7 \times 10^{-7} \text{ s}^{-1}$. Considering that the total flux on the surface of the satellite is $\frac{4}{3} \Phi$ the solar flux, we obtain a global mean photo-destruction rate of $1.8 \times 10^{-7} \text{ s}^{-1}$, averaged over time and latitude, implying a lifetime of $\sim$1500 h. Variations of solar activity and the eccentricity of Jupiter’s orbit will cause temporal changes of $\sim$40% in the rates (Woods and Rottman, 2002), while variations due to temperature between high and low latitudes should be much smaller, as judged from our data of Fig. 5.

4.3. Comparison with charged particle irradiation

The amount of hydrogen peroxide in water ice at Europa and other icy satellites is given by the competition between the formation rate (mostly by charged magnetospheric particles) and the destruction rate by particles and solar UV. The photolytic production of $\text{H}_2\text{O}_2$ from water is negligible since it requires wavelengths shorter than $\sim$160 nm, where the solar flux is small and, even for Lyman-$\alpha$ the equilibrium column density formed can be calculated to be $\sim 4 \times 10^{15} \text{ cm}^{-2}$ from photochemistry experiments at 10 K (Gerakines et al., 1996) using $5.7 \times 10^{-17} \text{ molecule}^{-1}$ for the strength of the 3.5 $\mu\text{m}$ absorption band (Loeffler et al., 2006b). Such column density is 20–400 times smaller than the estimated value at Europa (Carlson et al., 1999) and limited to the shallow penetration depth of Lyman-$\alpha$ ($\sim$40 nm).

The formation of $\text{H}_2\text{O}_2$ by magnetospheric ions and electrons can be obtained by using a radiolytic yield, $G$ (in molecules per 100 eV deposited): $G(\text{H}_2\text{O}_2) = 0.36$ for ions (Loeffler et al., 2006b) with high stopping power, and $0.028–0.051$ for weakly ionizing $10 \text{ keV}$ electrons at $80–100 \text{ K}$ (Hand and Carlson, 2011). The sensitivity of $\text{H}_2\text{O}_2$ production to the density of energy deposition is discussed by Burns and Sims (1981) and Loeffler et al. (2006b). Using proton fluxes collected by Cooper et al. (2001) and $G(\text{H}_2\text{O}_2) = 0.36$, since the peak proton energy at Europa is $\sim 100 \text{ keV}$ (Paranicas et al., 2002) we obtain an areal $\text{H}_2\text{O}_2$ production rate (in units of $10^3 \text{ cm}^{-2} \text{s}^{-1}$) of 40 at Europa, 4 (0.1) at Ganymede’s poles (equator), and 0.08 at Callisto. The variation among these satellites is determined by their proximity to Jupiter and the existence of a local magnetic field at Ganymede. We note that on all satellites the $\text{H}_2\text{O}_2$ production rate may be slightly higher as heavy ions and high energy electrons will also contribute to $\text{H}_2\text{O}_2$ production.

The destruction of $\text{H}_2\text{O}_2$ by magnetospheric protons at Europa was calculated by Loeffler et al. (2006b) as $8.9 \times 10^{-7} \text{ s}^{-1}$, which is $\sim$5 times higher than the global mean photodestruction rate calculated above. Thus, at Europa, the abundance of hydrogen peroxide is mainly determined by ion impacts. At the other jovian icy satellites, where particle fluxes and hence the $\text{H}_2\text{O}_2$ are much lower, photodestruction limits concentrations of hydrogen peroxide to much lower than the 0.0013 value for Europa’s leading hemisphere, which may explain the absence of detection of this molecule on the other jovian satellites.

On Enceladus, as the energetic proton flux is very low (Paranicas et al., 2008), $\text{H}_2\text{O}_2$ production is likely dominated by energetic electrons, which are $\sim$10 times less efficient in producing $\text{H}_2\text{O}_2$ than keV protons. Using an average G value of 0.04 (Hand and Carlson, 2011), we estimate that the areal $\text{H}_2\text{O}_2$ production rate from energetic electrons is $\sim 2 \times 10^3 \text{ cm}^{-2} \text{s}^{-1}$ for the nominal (averaged) flux given in Cooper et al. (2009), or about a factor of 200 lower than on Europa. Given that the solar flux would only be attenuated by a factor of 3.2, compared to the jovian satellites, we expect that the absence of $\text{H}_2\text{O}_2$ on Enceladus is likely due to the high efficiency of photodestruction.

Finally, due to the high transparency of water in the UV above 180 nm, solar irradiation will reach depths much deeper than where most radiolysis products are formed, effectively bleaching depths on the order of millimeters for those molecules that diffuse deeper in the ice. The photodestruction of $\text{H}_2\text{O}_2$ at greater depths ($\sim$cm), where higher energy electrons ($\sim$10 MeV) can form $\text{H}_2\text{O}_2$, is likely less important due to scattering caused by grains and absorption caused by other species mixed in the grains.

5. Conclusions

In this work, we have used infrared spectroscopy and microbalance gravimetry to study the photodecomposition by 193 nm photons of $\text{H}_2\text{O}_2$ in solid $\text{H}_2\text{O}_2+\text{H}_2$ mixtures at temperatures between 21 and 145 K. We find that the area of the 3.5 $\mu\text{m}$ infrared absorption of $\text{H}_2\text{O}_2$ decreases with photon fluence at all temperatures studied, and that the destruction rate is lowest at 70 K. Microbalance gravimetry indicates that the loss of $\text{H}_2\text{O}_2$ observed in the infrared cannot be due to photodesorption and thus must be due to photodestruction of the $\text{H}_2\text{O}_2$. To quantify the photodestruction of $\text{H}_2\text{O}_2$, we developed a two-component model that adequately fits our data and yields a destruction cross section for each temperature studied.
Extrapolating our results to the icy satellites, we find that the presence of H$_2$O$_2$ on Europa is consistent with our results, as the photodestruction rate is lower than the average ion destruction rate. However, on Ganymede and Callisto, given that the photodestruction rate is essentially the same as it is on Europa and that the ion energy flux (and hence H$_2$O production rate) is significantly lower, we conclude that the UV light will effectively lower the equilibrium concentration of H$_2$O on the surface by at least a factor of five making H$_2$O$_2$ much more difficult to detect. Similarly on Enceladus we estimate that the H$_2$O production rate is ~200 times lower than on Europa, and thus since the photodestruction rate is only about three times lower, we suggest that the absence of H$_2$O on the surface of Enceladus is likely due to the high efficiency of photodestruction. Finally, given that the photodestruction of H$_2$O$_2$ clearly plays a role in determining its equilibrium concentration on the icy satellites, predicting what satellites will have H$_2$O will come down to characterizing the ionizing radiation environment at the surface, as well as other factors such as the composition.

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