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

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**A R T I C L E  I N F O**

Article history:
Received 15 March 2013
Revised 11 June 2013
Accepted 24 June 2013
Available online 16 July 2013

Keywords:
Europa
Ices, IR spectroscopy
Jupiter, satellites
Saturn, satellites
Photochemistry

**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 μm 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 μm 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 μm 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, there have been a few gas phase detections of H$_2$O$_2$. For instance, H$_2$O$_2$ has been detected in Mars’ atmosphere using both submillimeter (Clancy et al., 2004) and infrared spectroscopy (Encrenaz et al., 2004). Interestingly, the abundance of H$_2$O$_2$ 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 H$_2$O$_2$ up to the previous detected levels (Hartogh et al., 2010). Most recently, using submillimeter spectroscopy gas phase H$_2$O$_2$ has been detected in the interstellar medium (Bergman et al., 2008) and can thus penetrate deeply into the surface ice. To test this possibility, we have photolyzed low concentrations of H$_2$O$_2$ in solid H$_2$O mixtures with UV photons (193 nm), which are weakly absorbed by water (~2 cm$^{-1}$ 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 H$_2$O$_2$ in solid H$_2$O mixtures with UV photons (193 nm) at temperatures between 21 and 145 K. During photolysis, we have measured the photodestruction of H$_2$O$_2$ 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 areal mass (mass/area) of the films was determined (153 μg/cm$^2$–2 μm) by the change in the resonance frequency of the crystal, which was measured with an Inficon IC5 controller to a resolution of 0.1 Hz (Sack and Baragiola, 1993). The measured areal mass can be converted to film column density η (molecules/cm$^2$) if the film composition is known, and converted to thickness if the mass density is known (Sack and Baragiola, 1993).

The H$_2$O–H$_2$O$_2$ mixtures were grown from a liquid solution of hydrogen peroxide and water using a glass doser (Loeffler and Baragiola, 2005). Each film contained between 0.5% and 2% H$_2$O$_2$, which was calculated from the band area of the infrared H$_2$O$_2$ 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.

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 MgF$_2$ 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 × 10$^{15}$ photons/cm$^2$/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 feature 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 H$_2$O$_2$ absorption band is very weak at high fluences, and thus here we analyze the derivative of the optical depth (~ln reflectance) spectrum. Fig. 2 shows that the absorption feature is more pronounced in the derivative, making quantification of small values (high fluences) more accurate. As the H$_2$O$_2$ absorption band does not change shape as it attenuates during photolysis, analysis using the band area or the derivative peak height yielded the same results within 5% over the region where a band area could be accurately calculated. Thus, data shown here will be given as the normalized peak-to-peak height of the derivative, which is obtained after subtracting the continuum baseline.

3. Results

Fig. 1 shows the infrared spectrum of our H$_2$O + H$_2$O$_2$ mixture before, during and after UV photolysis at 100 K between 3000 and
The normalized results for all the temperatures studied are shown in Fig. 3. In all cases, the H$_2$O$_2$ decreases with laser fluence and continues to decrease at the two higher temperatures, consistent with radiolysis studies on H$_2$O$_2$ (Warren and Brandt, 2008), and thus only ~0.00003% of light is absorbed by H$_2$O. Unlike water, the absorption band of H$_2$O$_2$ decreases during photolysis. However, no new absorption bands, such as those of HO$_2$ or HO$_3$, 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 H$_2$O$_2$ 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 H$_2$O$_2$, we analyzed the peak-to-peak of the derivative of the 2860 cm$^{-1}$ absorption band of H$_2$O$_2$ during photolysis. The normalized results for all the temperatures studied are shown in Fig. 3. In all cases, the H$_2$O$_2$ decreases with laser fluence and continues to decrease at the highest doses used in this experiment. Interestingly, the rate of H$_2$O$_2$ destruction appears to be highest at the lowest temperature, consistent with radiolysis studies on H$_2$O$_2$ + H$_2$O mixtures (Hudson and Moore, 2006) at 19 and 80 K. However, as the temperature is increased above 70 K, the destruction rate of H$_2$O$_2$ also increases. From Fig. 3, we can determine the fluence needed to destroy half of the H$_2$O$_2$ in the sample, $F_{1/2}$, and have shown these values in Table 1. One can see from Table 1 that the range of calculated $F_{1/2}$ 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 $T \leq 130$ K, where thermal sublimation of H$_2$O is negligible. Assuming the mass loss is entirely due to H$_2$O$_2$, we estimate the yield to be $\sim 1-4 \times 10^{-6}$ H$_2$O$_2$/photon. Comparing these values to $F_{1/2}$ given in Table 1, we estimate that at most only about 3% of the H$_2$O$_2$ in the sample would be lost due to photodesorption by $F_{1/2}$, suggesting that the decrease in the infrared band area observed (such as in Fig. 1) is due to photodestruction and not photodesorption. Thus, the lack of detected decomposition products in Fig. 1 is likely a combination of the initial low H$_2$O$_2$ 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 H$_2$O$_2$ done at temperatures relevant to the outer Solar System, have focused on the analysis of the electron paramagnetic resonance spectra of OH and HO$_2$ radicals, e.g., Wyard et al. (1968), Harrison and Symons (1993), and Beine and Anastasio (2011). Several interesting experiments have been performed with H$_2$O$_2$ isolated in rare gas matrices (e.g., Khraichtchev 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, as we observe no apparent changes in H$_2$O infrared absorption bands during photolysis (Fig. 1) and note that H$_2$O is essentially transparent to the 193 nm light, we neglect the initial role of water and consider only photoabosorption by H$_2$O$_2$. 

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**Table 1**

<table>
<thead>
<tr>
<th>T (K)</th>
<th>H$_2$O$_2$ + H$_2$O</th>
<th>N (10$^{19}$ photons/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>3.2</td>
<td>0.5</td>
</tr>
<tr>
<td>130</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>9.9</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1.9</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Example of the derivative spectrum (solid curve) and the featureless continuum fit used (dashed curve) for a H$_2$O + H$_2$O$_2$ mixture after being photolyzed with 50 x 10$^{19}$ photons/cm$^2$ at 100 K. Inset: all derivative spectra taken during photolysis at 100 K; the derivative peak to peak height decreases as the H$_2$O$_2$ in the sample decreases.

Fig. 3. Destruction of H$_2$O$_2$ in a H$_2$O + H$_2$O$_2$ mixture photolyzed at different temperatures. The solid line is a fit to the experimental data using Eq. (7). The curves tend asymptotically to a constant value. At the two higher temperatures the value cannot be distinguished from zero within fitting errors.
Photoabsorption at 193 nm occurs with a cross section (in cm² 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 (Grinevald et al., 1986). Alternatively, the H–OOH bond may be broken, leading to a H atom and HO₂ (Gerlach-Meyer et al., 1987), as in (2) below:

\[
\begin{align*}
\text{hv} + \text{H}_2\text{O}_2 & \rightarrow \text{OH} + \text{OH} + 4.3 \text{ eV} \quad (80\%) \\
\text{hv} + \text{H}_2\text{O}_2 & \rightarrow \text{HO}_2 + \text{H} + 2.5 \text{ eV} \quad (20\%)
\end{align*}
\]

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 \( \text{OH} + \text{OH} \rightarrow \text{H}_2\text{O}_2 \) and \( \text{H} + \text{HO}_2 \rightarrow \text{H}_2\text{O}_2 \). 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 \( \text{H}_2\text{O}_2 \) concentration is sufficiently high and diffusion allows collision of radicals and further hydroxyl fragments rotating in opposite sense around the O–O axis (Grunewald et al., 1986). The O atom produced in reaction (13) may be important for the production of other secondary products, such as \( \text{O}_2 \) or \( \text{O}_3 \), while photoabsorption by \( \text{HO}_2 \) results in the formation of \( \text{H}_2\text{O}_2 \) by the exothermal reactions \( \text{OH} + \text{OH} \rightarrow \text{H}_2\text{O}_2 \) and \( \text{H} + \text{HO}_2 \rightarrow \text{H}_2\text{O}_2 \). 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).

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

\[
P = H = 2[\rho_0 - \rho]
\]

where \( \rho_0 \) is the initial column density of hydrogen peroxide. We then can rewrite (5) in terms of only the hydrogen peroxide column density:

\[
d\rho /dF = -\sigma \rho + \sigma \rho_2 \rho_0 - \rho
\]

We can integrate (11) to obtain:

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

\[
a = \sigma [1 - 2\rho_0]; \quad b = 2\rho_0 \sigma
\]

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 \( \text{H}_2\text{O}_2 \) can be reformed by hydroxyl 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 (Lunik and Sedlak, 1992):

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

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

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

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

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

The O atom produced in reaction (13) may be important for the production of other secondary products, such as \( \text{O}_2 \) or \( \text{O}_3 \), 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

\[
\frac{d\rho}{dF} = -\sigma \rho + \sigma \rho_2 \rho_0 - \rho
\]

\[
\text{Fig. 4. Photodestruction cross section for the H}_2\text{O} + \text{H}_2\text{O}_2 \text{mixture as a function of temperature.}
\]
jovian system by dividing by the square of the distance. To arrive at the destruction cross section, we first calculate the photoabsorption rate as the integral of the photon flux and the absorption cross section $\sigma_a$, given by Lin et al. (1978) above 189 nm for aqueous solutions and by Suto and Lee (1983) for gaseous H$_2$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 photoabsorption cross-section, and the differential absorption rate per nm. The integral of the latter curve gives an absorption rate of $7 \times 10^{-9}$ 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 photoabsorption cross section of $1.3 \times 10^{-18}$ cm$^{-2}$ at 193 nm (Lin et al., 1978). For an average equatorial temperature of 106 K appropriate to Europa (Spencer et al., 1999), $\Phi \approx 0.1$. 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 flux) photodestruction rate at Europa at the subsolar point is $7 \times 10^{-2}$ s$^{-1}$. Considering that the total flux on the surface of the satellite is $\frac{1}{4}$ the solar flux, we obtain a global mean photodestruction rate of $1.8 \times 10^{-7}$ 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 H$_2$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 $\sim 4 \times 10^{15}$ cm$^{-2}$ from photochemistry experiments at 10 K (Gerakines et al., 1996) using $5.7 \times 10^{-17}$ molecule$^{-1}$ for the strength of the 3.5 $\mu$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 H$_2$O$_2$ by magnetospheric ions and electrons can be obtained by using a radiolytic yield, $G$ (in molecules per 100 eV deposited): $G$(H$_2$O$_2$) = 0.36 for ions (Loeffler et al., 2006b) with high stopping power, and 0.028–0.051 for weakly ionizing 10 keV electrons at 80–100 K (Hand and Carlson, 2011). The sensitivity of H$_2$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 $G$(H$_2$O$_2$) = 0.36, since the peak proton energy at Europa is $\sim 100$ keV (Paranicas et al., 2002) we obtain an areal H$_2$O$_2$ production rate (in units of $10^3$ cm$^{-2}$ 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 H$_2$O$_2$ production rate may be slightly higher as heavy ions and high energy electrons will also contribute to H$_2$O$_2$ production.

The destruction of H$_2$O$_2$ by magnetospheric protons at Europa was calculated by Loeffler et al. (2006b) as $8.9 \times 10^{-7}$ 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 H$_2$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), H$_2$O$_2$ production is likely dominated by energetic electrons, which are $\sim 10$ times less efficient in producing H$_2$O$_2$ than keV protons. Using an average G value of 0.04 (Hand and Carlson, 2011), we estimate that the areal H$_2$O$_2$ production rate from energetic electrons is $\sim 2 \times 10^3$ cm$^{-2}$ 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 H$_2$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 H$_2$O$_2$ at greater depths ($\sim$cm), where higher energy electrons ($\sim$10 MeV) can form H$_2$O$_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 H$_2$O$_2$ in solid H$_2$O$_2$ + H$_2$O mixtures at temperatures between 21 and 145 K. We find that the area of the 3.5 $\mu$m infrared absorption of H$_2$O$_2$ decreases with photon fluence at all temperatures studied, and that the destruction rate is slowest at 70 K. Microbalance gravimetry indicates that the loss of H$_2$O$_2$ observed in the infrared cannot be due to photodesorption and thus must be due to photodestruction of the H$_2$O$_2$. To quantify the photodestruction of H$_2$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 on Europa is consistent with our results, as the photochemical production rate is lower than the average ion destruction rate. However, on Ganymede and Callisto, given that the photodestruction rate is significantly lower, we conclude 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 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.

Acknowledgments

This work is being funded by NASA Outer Solar System Program. M. Loeffler thanks J. Cooper and P. Gerakines for useful discussions.

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