Laboratory studies of the optical properties and stability of oxygen on Ganymede

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Abstract. We present measurements of the optical properties of solid O$_2$ and O$_2$:H$_2$O films and on the stability of oxygen in water ice at different temperatures. The experiments are meant to test hypotheses for the location of condensed molecular oxygen in Ganymede. We find that oxygen is not retained in water ice at Ganymede’s recorded surface temperatures and analyze current questions associated with the existence of oxygen in this Jovian moon. The results suggest that solid oxygen and possibly other condensed gases exist on cold patches on the heterogeneous Ganymede’s surface.

1. Introduction

The surface composition of icy satellites is currently deduced mainly from how they appear under sunlight. Reflectance spectra have been measured by ground space telescopes, the Hubble Space Telescope, and spacecraft instruments. The current interpretation of the spectra relies heavily on theoretical modeling because of the dearth of laboratory experiments that simulate the conditions that may occur at these satellites. Many factors affect reflectance and are not well understood. Among them are porosity, surface roughness, and light absorption by impurities and by products of the interactions of energetic particles and radiation with the surface. Following our studies of the effect of energetic ion and photon bombardment on the surface of the Galilean satellites [Sack et al., 1991, 1992, 1993; Shi et al., 1995; Westley et al., 1995a, 1995b] we have recently been interested in the surface composition of Ganymede [Vidal et al., 1997]. Early work on this satellite has been summarized by Clark et al. [1986] and Calvin et al. [1995]. Infrared spectra show that the surface of Ganymede consists mainly of water ice, with an estimated visible optical depth of a few hundred microns [Clark, 1980; Calvin et al., 1995]. Analysis of the reflectance has suggested a very porous surface (~80% void space) [Buratti, 1991, 1995], but the results are model dependent [Domingue and Verbiscer, 1997]. The reddening produced by the drop of reflectance at short wavelengths is thought to be due to non-ice components, some of which have been recently identified [McCord et al., 1997].

An interesting and significant development in our understanding of Ganymede’s surface composition came from the discovery of absorption features in the reflectance spectrum that signal the presence of condensed oxygen [Spencer et al., 1993; Calvin and Spencer, 1997] and ozone [Nelson et al., 1987; Noll et al. 1996]. Possibly linked to the much higher absorbance—and thus detectability—of ozone compared to condensed O$_2$, condensed O$_3$ has been identified also in Saturn’s satellites Rhea and Dione [Noll et al., 1997] while condensed O$_2$, a likely precursor to O$_3$, has not been detected in other satellites. The absorption structures (bands) in the reflectance that indicate condensed oxygen are in the red, and arise from the weak absorption of a photon by two adjacent O$^2_2$ molecules, (O$_2$)$_2$; double transitions from the ground $X^2\Sigma_g^-$ state to the first excited state $a^1\Delta_u$ with vibrational quantum number 0 or 1 (0-0 and 1-0 bands). The shape and position of the O$_2$ absorption bands further indicate that the oxygen molecules are in the solid state; this implies temperatures lower than 35 K, much lower than the reported daily surface temperatures of Ganymede (90-152 K [Orton et al., 1996]). If this puzzle were solved by some unspecified interaction that would cause the band shapes of oxygen at Ganymede’s expected surface temperatures to resemble the observed bands in the satellite, another puzzle would result. The vapor pressure of oxygen at temperatures above 90 K, > 1 bar, is at variance with the very low atmospheric pressures (10$^{-3}$-10$^{-8}$ mbar) derived from stellar occultation measurements [Carlson et al., 1973; Broadfoot et al., 1979].

The distribution of the condensed oxygen on Ganymede is not uniform. The (O$_2$)$_2$ absorption bands are more prominent on the trailing hemisphere, which was assumed to be subject to considerable bombardment by ions from the Jovian magnetosphere [Calvin et al., 1996]. The oxygen bands are more prominent near the equator and absent near the poles [Calvin and Spencer, 1997]. These observations led to speculation that oxygen is trapped in the surface ice in the form of gas bubbles generated by radiolysis of water ice induced by magnetospheric and high-energy ion bombardment [Spencer et al., 1995; Calvin et al., 1996; Johnson and Jesser, 1997]. As we will discuss below, this assumption presents a number of difficulties. It does not account for out-diffusion of trapped oxygen, nor the mismatch of band shapes and depths, nor an insufficient flux of bombarding ions. The latter difficulty became apparent after the discovery of a magnetic field at Ganymede by the Galileo probe [Kivelson et al., 1996, 1997; Williams et al., 1997]. This field likely prevents most of the magnetospheric ions from reaching the satellite except near polar latitudes, which is where condensed (O$_2$)$_2$ was not detectable. This suppression of a large magnetospheric flux, which needs to be confirmed by detailed modeling, means that sputtering processes are much weaker than previously assumed [e.g., Shi et al., 1995] and is likely

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the reason for the absence of a sodium atmosphere around Ganymede [Brown, 1997]. The magnetic field would also eliminate magnetospheric bombardment as the cause of leading-trailing hemispheric asymmetry in the amount of \( \text{O}_2 \), which would rather be likely related to differences in micrometeorite bombardment.

Recent studies in our laboratory showed that most of the oxygen trapped in bubbles in oxygen-water mixtures condensed at 27 K diffuses out of ice above 40 K [Vidal et al., 1997]. The oxygen that remains trapped was undetectable by light absorption in the red. Accurate measurements of the band shapes and positions showed a good match between Ganymede and pure condensed oxygen. The bands from oxygen trapped in ice are shifted with respect to the satellite's bands [Spencer et al., 1995] well outside the experimental error. However, recent measurements with the Hubble Space Telescope [Calvin and Spencer, 1997] suggest variations in band position with latitude, but the low signal to noise ratio does not allow conclusive comparisons with laboratory experiments. In any case, the observations imply that Ganymede's bands are from a source of condensed oxygen at temperatures much lower that the reported surface temperature. This source was conjectured to be a cold subsurface or an atmospheric haze [Vidal et al., 1997]. Because of temperature variations during the orbital cycle, and time of day, such oxygen sources would lead to a variable oxygen atmosphere on the satellite that could be probed by observing star occultations at different latitudes and times.

To answer some of the questions, we undertook new laboratory experiments using thicker films than in our previous studies. We also tried to retain oxygen in water ice above 100 K, at least temporarily, by capping ice mixtures with a thick layer of water ice, to obtain reflectance spectra. The experiments, to be described below, confirm the conclusion that condensed oxygen is not retained in ice at the recorded daily temperatures of Ganymede's equatorial region in sufficient amounts to produce the absorption band depth seen in the telescopic observations.

2. Experiments

The experiments were made in an oil-free stainless steel chamber [Sack and Baragiola, 1993] that achieves ultrahigh vacuum with cryopumps. The base pressure is in the \( 10^{-10} \) mbar range but additional pumping provided by a cold shield surrounding the target keeps the target environment at a pressure estimated to be an order of magnitude smaller. The ice films were grown by condensing pure gases on a cold substrate at a rate of \( \sim 10 \) mm/s. The gas doser is a microcapillary array, which directed a uniform and collimated stream of gas onto the cold substrate at normal incidence. The gases were either pure oxygen or \( 1:1 \) \( \text{O}_2 : \text{H}_2 \text{O} \) mixtures. The substrates we used were an optically flat gold mirror or a standard barium sulfate white surface. The film thickness was measured with a calibrated quadrupole mass spectrometer that measured the gas evolving from the films during warm up. An independent determination was made from the total quantity of gas condensed on the film, calculated from the decrease of pressure in the manifold feeding the gas doser, and the area of the deposit. Both determinations agreed to within 20%.

Bidirectional reflectance was measured at a 45° or 90° phase angle using a quartz-halogen lamp. In the first case the incidence and emergence angles were 32° and 13° with respect to the normal to the surface; in the second case the angles were 35° and 55°. The reflected light was analyzed using a grating spectrometer equipped with a CCD detector, working at a resolution of 20 Å. The wavelength scale was calibrated to within 1 Å using Ne and Hg reference lamps. To remove the shape of the lamp spectrum and spectrometer efficiency function, the spectrum of the reflected light was divided by that of a reference surface, either a thick pure ice film or the standard white reflector. We call this ratio the reflectance \( R \). We note that the reflectance of a thin film may differ from that of a bulk sample because of a different distribution of optical path lengths.

We made several experiments with films made of pure oxygen and water-oxygen mixtures, and with films capped with a layer of water ice several microns thick. It is important to comment on the appearance of the films since laboratory ice samples are often more scattering than those expected on icy satellites. This usually has been interpreted to signal the presence of small grains intrinsic to the vacuum deposition process. However, Westley et al. [1998] found very small light-scattering coefficients incompatible with the existence of many grain boundaries, but expected from glassy, amorphous ice. This high optical quality was also seen in ice films formed slowly at temperatures known to result in cubic ice. On the other hand, fractures in the ice films, which make them highly scattering [Westley et al., 1998], may result from stresses produced when the ice density changes during the collapse of micropores [Mayer and Pletzer, 1986; Rowland and Devlin, 1991] or phase transformations. Fracturing of shattering of the thin films depends on their elastic coupling to the substrate. It is more likely to occur in thick samples deposited on rigid substrates than on films deposited on the very thin and flexible gold-coated quartz membranes used in the present experiments and those by Westley et al. [1998]. In our previous simulations of magnetospheric bombardment effects on reflectance [Sack et al., 1991, 1992, 1993], we used thick ice films deposited on rigid substrates; those ice films appeared frosty, possibly due to multiple fractures. In the current experiments, visual inspection of the ice films of water or water-oxygen mixtures up to \( \sim 3 \) mm thick showed them to be highly transparent (less scattering than pure oxygen films); the optical band depth corresponds to path lengths near a millimeter. For these thick films we could see with the bare eye tiny needle-like surface structures also reported by others [Mayer and Pletzer, 1986; Lauffer et al., 1987; Bar-Nun et al., 1988]. We note that the needles remain in the ice when it is heated until the film is removed, meaning that this type of morphology may exist in the surface of icy satellites. These needles could be the complex textures that Verbriscer and Veverka [1990] invoke to explain the less forward light scattering from satellite grains than from terrestrial snow.

Figure 1 shows the spectrum of light reflected from a 90 μm oxygen film grown on barium sulfate, taken at 25 K, and normalized to the spectrum from the bare substrate. The film was grown at 24–25.4 K at a rate of 0.53 μm/min. In addition to the bands seen on Ganymede, other smaller bands appear that have previously been seen in transmission experiments
Figure 1. Ratio of light reflected from a 90 μm thick solid oxygen film grown at 24-25.4 K normalized to that reflected from the barium sulfate substrate. The measurements were done at 25 K.

using thick samples [Landau et al., 1962]. They correspond to transitions from the ground state of doubly excited states: 2 \( ^1\Delta_g (v=2) \) at 3312±4 Å, \( ^1\Sigma_g^+ \ 1\Delta_g (v=0) \) at 4760±10 Å, and 2 \( ^1\Sigma_g (v=1,0) \) at 3620±10 and 3785±10 Å, respectively. Though weaker than the main bands in the red, these bands should also be observable in low noise spectra of Ganymede. Using an absorption length of 10 cm\(^{-1}\) at the 1-0 band minimum [Landau et al., 1962; Vidal et al., 1997], the optical path length in the film is 520 μm, about twice as large as would be expected in the absence of scattering, consistent with the cloudy visual appearance of the film.

To study oxygen diffusion through ice we formed a 2.8 mm thick 1:1 O\(_2\):H\(_2\)O film at 20.8-22.6 K at a rate of 0.5-2.2 μm/min and capped it with a 25 μm thick water ice layer grown at 22 K, at a rate of 1.8 μm/min. The idea was to see if more oxygen could be retained in the ice than in our previous experiments [Vidal et al., 1997]. We then heated the sample at 0.5 K/min while the mass spectrometer recorded the evolution of oxygen. Figure 2 shows the oxygen pressure as a function of temperature. At low temperatures, oxygen outgassing appears to follow an Arrhenius law with an activation barrier of 6 meV. Outgassing accelerates above ~40 K, passes through a maximum, and then decays to a low level until one approaches the crystallization temperature. During the diffusion process a significant amount of oxygen is trapped in the ice. The total amount trapped is 10-15% volume as derived from the large desorption peaks that occur at temperatures around 147 K and 165 K, close to phase transitions from amorphous to cubic and cubic to hexagonal [Vidal et al., 1997].

Figure 3 shows reflectance spectra measured at 22 K, after finishing the deposition of the ice cap. For these very thick ice films, structure in the response function of the spectrometer is not cancelled completely when taking reflectance ratios. The broad shoulder seen at around 6000 Å, not present in thinner films, is most likely the Chevannes band of ozone [Amoruso et al., 1990], formed by photolysis with UV photons from the lamp used in this study.

Figure 3 shows spectra taken for the film warmed up to 70 K. After ramp heating to 85 K, we took the mixed ice to 100 K and let it stay at that temperature for 13 hours. During this time, we noticed that the outgassing rate, although low, remained stable keeping the pressure in the vacuum chamber at about 10\(^{-7}\) mbar. This pressure corresponds to an

Figure 2. Thermal desorption spectra of oxygen for a 2.8 mm 1:1 H\(_2\)O:O\(_2\) film deposited capped with 25 μm H\(_2\)O. The deposition temperature was 20.8-22.6 K.

Figure 3. Spectra of light reflected from a 2.8 mm 1:1 H\(_2\)O:O\(_2\) film, as deposited at 22 K, after heating to 70 K and after heating to 120 K. The spectra are normalized to that of the same sample after it was heated to 160 K to remove all the oxygen.
outgassing rate of the order of $10^{15}$ molecules/cm$^2$/s or the equivalent of 30 µm/d of solid oxygen. This implies that oxygen-containing ice will lose the oxygen if left in vacuum for a sufficiently long time. Our results for oxygen-ice mixtures are similar to other work on CO trapped in water ice [Schmitt et al., 1988; Kouchi, 1990] in two aspects. First there is a maximum concentration of 10-15% for storing gases in ice below 130 K, irrespective of the initial gas to water ratio. Second, the gas continuously leaks out of the ice even at temperatures below those needed to convert amorphous ice to the cubic form. We note that oxygen outgassing is not limited to amorphous ice, since oxygen loss is continuous at any temperature above 130 K, where ice crystallizes rapidly. For ice in an environment at any finite pressure, there will be an equilibrium between outgassing and incorporation from the gas phase. This is why common household refrigerator ice can keep gas bubbles at atmospheric pressure.

We measured optical spectra while warming the mixed ice film, which caused the band depths to decrease continuously. A reflectance spectrum taken at 120 K is shown in Figure 3; the absorption bands were reduced significantly compared with those of ice at 70 K and became undetectable above the noise in about 30 min. Figure 4 shows the band depths \(-\ln(R)\) as functions of temperature, where \(R\) is the reflectance defined above, taken at the band minimum (\(R=1\) for ice without oxygen.) The drop is primarily related to oxygen loss (see Figure 2) and the decrease of absorption strengths [Landau et al., 1962; Vidal et al., 1997], but it may be also affected by temperature-induced changes in the density of light-scattering centers.

Figure 5 shows details of the oxygen bands, taken under different conditions, in comparison with the bands seen on Ganymede. The bands are normalized to ease comparison of their shapes. We confirmed the previous results at low temperatures, which showed that the spectra of solid oxygen have the better agreement with Ganymede’s [Vidal et al., 1997]. In addition, we notice that at 120 K, a typical recorded temperature in Ganymede’s equatorial region, the laboratory bands have the worst agreement with the satellite’s spectra; they are too narrow and shifted to longer wavelengths. Figure 6 shows the band positions versus temperature; it can be seen that the 0-0 band is the one most affected by temperature, suggesting that it is the best to use to diagnose the state of condensed oxygen. It is also clear from the figure that oxygen trapped in bubbles in ice at 70-120 K, the surface temperatures recorded by the Galileo radiometer, cannot be the source of the satellite’s oxygen features.

3. Discussion

Many questions are posed by the observations on Ganymede. Does the molecular oxygen result from radiolysis of atmospheric water or of surface ice? Where does the condensed oxygen lie, in bubbles in the ice, or is it condensed in cracks or crevices, in a deep layer, or in an atmospheric haze? What is the phase of the oxygen, solid, liquid, or gaseous? What are its column density and its temperature? Some possible answers to these questions are starting to come from laboratory experiments.

To know the column density of condensed oxygen in Ganymede one needs to know its phase, as well as the optical path length. The absorption strength depends drastically on the phase of oxygen, decreasing by orders of magnitude going from the solid phases to the liquid and gas phases [Dianov-Klokov, 1950, 1964; Landau et al., 1962; Tabisz et al., 1969; Greenblatt et al., 1990]. The large variation of absorption strength with temperature will favor observations from cold regions, an effect probably more important than the increase of optical depths expected at higher temperatures. This means that additional factors are at play that restrict the (O$_2$)$_2$ bands to the equatorial regions. Using disk-averaged band depths, the equivalent thickness of oxygen in Ganymede is about 20 µm, assuming the 0 phase of solid oxygen, or about 0.2 mm if oxygen is in the liquid phase [Calvin et al. 1996]. The quantity of oxygen is twice as large at the equator where the bands are deeper [Calvin and Spencer, 1997]. If oxygen is trapped in bubbles in the ice as a gas at Ganymede’s reported daily temperatures, a much larger quantity of gas is required. Oxygen at an assumed concentration of $10^{19}$ molecules/cm$^3$ [Johnson and Jesser, 1997], ~250 atm, will have an absorption coefficient ~60 times smaller than $\beta$ oxygen. If oxygen is diluted by being embedded in the ice to maximum concentrations of 15% in volume [Vidal et al., 1997], the optical depth of ice required at the equator will be more than a centimeter. Moreover, a concentration of 15% is too high for radiation induced gas bubbles; values of 3% were reported for the concentration of voids/bubbles by Heide and Zeiter [1985].

The likely origin for molecular oxygen is radiolysis. This includes photodesorption of ice from solar UV photons [Westley et al., 1995a, b], direct sputtering, and photodissociation of adsorbed or sputtered water molecules followed by
hydrogen escape [Yang and McElroy, 1977; Kumar and Hunten, 1982; Barth et al., 1997; Frank et al., 1997]. The amount of oxygen in the atmosphere is uncertain because the existing reports show a huge discrepancy. Carlson et al. [1973] gave a lower limit for the surface pressure of $10^{-7}$ mbar from two measurements of stellar occultation from Earth in the visible red that included ingress and egress of the star behind the moon. Broadfoot et al. [1979] measured the ingress in the occultation of a star with the Voyager spacecraft in the ultraviolet, between 912 and 1700 Å; the limb was near 180° longitude and 13:30 local time [Spencer, 1982]. The report, which does not show actual data, gave an upper limit of $10^{-8}$ mbar for gases which absorb significantly in the UV range measured, but does not rule out a denser atmosphere of gases such as nitrogen and argon. We note that this occultation was by a terrain that does not contain significant amounts of condensed oxygen [Calvin et al., 1996]. Even though the occultation occurred for the limb near noon, the upper limit derived for the atmospheric pressure is 1 order of magnitude lower than the vapor pressure of water ice at average midday temperatures reported. This suggests that the temperature of the ice is lower than the average surface temperature due to high visible albedo and infrared emission. Spencer [1987a, b] and Spencer et al. [1998] have already pointed out that Ganymede's ice may be significantly colder than the average surface temperature.

The existence of a significant, but not yet quantified atmosphere follows from other recent studies with the Galileo orbiter. They include the observation of an ionosphere [Gurnett et al., 1996], an oxygen aurora near the poles of the satellite [Hall et al., 1998], and relatively large fluxes of escaping hydrogen [Barth et al., 1997; Frank et al., 1997]. These latter studies have found that the escaping H flux is not accompanied by oxygen emission and concluded that the oxygen enrichment on Ganymede is equivalent to 0.25-1 mm per million years. This quantity of oxygen is distributed in an unknown way in the atmosphere, condensed on the surface and trapped by reactions with other elements to form stable compounds.

Atmospheric oxygen may slowly accumulate inside the naturally occurring micropores of amorphous ice or in voids formed by radiation damage. Although it is known that amorphous ice can trap gases efficiently below 110 K in its micropores [Mayer and Pletzer, 1986], trapped oxygen has very low optical activity [Vidal et al., 1997] most likely because of large intermolecular distances [Dianov-Klokov, 1962]. Thus absorption from the atmosphere into micropores will not build up sufficient oxygen in the ice to explain Ganymede's band depths. If the temperature of the ice gets closer to the temperatures reported for Ganymede's equatorial region, the micropores will collapse, as discussed below, and the ice will crystallize, releasing the trapped gas.

We cannot dismiss the possibility that some process, not yet considered, could enhance the rate of oxygen accumulation into the voids. For instance, oxygen atoms produced by gas-phase radiolysis may diffuse rapidly through ice and accumulate in where they associate into oxygen molecules forming stable bubbles. But even if the temperature of the ice is much lower than the values measured on Ganymede, the gas will slowly diffuse out, as shown in Figures 2 and 4. One should note that diffusion in ice condensed from the gas phase is 5 to 7 orders of magnitude faster than what may be
of the amount of oxygen generated by radiolysis requires knowing the $G$ value, which is the number of molecules produced per 100 eV of energy deposited by the ions in the ice. Johnson and Jesser [1997] used the only published value, $G = 0.15$; it came from an outdated report [Lefort, 1955] and has not been confirmed by any modern experiments performed with gas-free ice [e.g., LaVerne, 1989]. Furthermore, experiments of MeV ion irradiation of ice have not reported oxygen accumulation in the ice but rather oxygen desorption during irradiation, which stops when the irradiation is interrupted [Reimann et al., 1984]. Oxygen desorption is interpreted as radiation enhanced out-diffusion [Benit and Brown, 1990; Benit et al., 1991]. It may also result from the dissociation of H$_2$O, a molecule that is known to form and accumulate in ice during irradiation [Spinks and Woods, 1990; Westley et al., 1995a; Gerakines et al., 1996]. Any amount of oxygen accumulation must be very small since the ice films remain stoichiometric to within 2% during prolonged irradiation [Brown et al., 1978a, b; Cooper and Tombrello, 1984]. A lack of oxygen accumulation was determined when evaporating ice samples that were irradiated to high doses of 60 keV O$_2^+$ ions at 100 K [Vidal et al., 1997]. According to the $G$ value mentioned above, a 60 keV O$_2^+$ projectile should produce ~90 O$_2$ molecules by radiolysis in ice. Some O$_2$ molecules are indeed generated by fast ions but they come out during bombardment and are not seen to be retained in the ice. From our ion bombardment experiments, we can set a bound of 0.3 trapped O$_2$ molecules per incident ion, after accounting for ion implantation, projectile reflection and sputtering. This is more than 2 orders of magnitude smaller than the value assumed by Johnson and Jesser [1997]. All these irradiation experiments lead to the conclusion that radiolysis of ice is not an important mechanism for generating trapped bubbles of oxygen in the surface of the icy satellites in sufficient quantities to produce significant oxygen absorption bands.

This analysis does not imply that ion irradiation is irrelevant. Together with energetic solar photons, ion bombardment provides sputtered oxygen directly and also a sputtered water atmosphere from which oxygen can then be produced by impact dissociation. On the other hand, sputtering will efficiently remove oxygen condensed on very cold regions, except near the equator of Ganymede, where most of the magnetospheric ion flux may be prevented from reaching the surface by the satellite's magnetic field. This magnetic protection is not present in other icy satellites and may explain why condensed O$_2$ is not evident in their reflectance spectra. Ion bombardment is important near Ganymede's poles, where only a thin layer of condensed oxygen may result from the competition of deposition and sputtering, and may partially convert by radiation into ozone. Due to the strong absorption coefficient in the ultraviolet, the column density of O$_3$ needed to explain the observations of Noll et al. [1996] is 3 orders of magnitude smaller than that needed to produce the observed O$_2$ bands on Ganymede. We note also that ozone is much less volatile than O$_2$ and its presence as a surface crust may prevent condensed O$_2$ from evaporating too fast.

The laboratory experiments suggest that condensed oxygen on Ganymede resides in regions with temperatures much lower than the average values reported. It is important to note that the temperatures measured by radiometers, like Voyager infrared imaging spectrometer (IRIS) or Galileo photopola rimeter-radiometer (PPR), are averages over areas of tens of

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**Figure 6.** Band positions versus temperature. Circles, this work, triangles, data from Vidal et al. [1997]. The solid symbols correspond to pure oxygen; the open symbols to the 1:1 water:oxygen film of Figure 2. The horizontal lines labeled G represent the disk averaged data for Ganymede measured by Spencer et al. [1995], extending to the range of recorded daylight temperatures.
thousands of square kilometers in size, which are thermally heterogeneous [Spencer 1987a, b]. In a body with a tenuous atmosphere, topography and other surface characteristics can cause large local temperature variations. Radiometers that operate at wavelengths near the peak of the thermal radiation spectrum have very small sensitivity to cold patches, due to the very strong dependence of Plank’s radiation function on temperature. This leads to a “slope” in the measurements, with lower temperatures at longer wavelengths [Spencer, 1987b]. The very low brightness temperatures measured at 6 cm, 55±6 K [de Pater et al., 1984] come from a better average of warm and cold areas, although the comparison with infrared measurements is not direct, since sampling depths are different.

Areas with a very high albedo or that are in the shadow many hours of the day, such as cracks or crater floors, may get cold enough to act as traps for atmospheric oxygen. The cracks, which could be ubiquitous, may be induced by wide thermal excursions, electrostatic charging, tidal forces, etc. Oxygen condensed in these very cold patches would be a source of the oxygen bands seen in reflectance during the part of the day when they are illuminated by the sun. Since the symmetric oxygen molecule has extremely low light absorbance in the visible and infrared, heating of the condensed oxygen by sunlight is indirect, through conduction from the ground on which it resides. Since solid oxygen is highly scattering, as found by Landau et al. [1962] and in this study, it is expected to have a very high albedo and therefore act as a thermal shield for the underlying material. Oxygen evaporated during the day will be replenished through the night only in the coldest regions, where it can condense. A consequence of the existence of the very cold regions is that other gases like ozone and CO₂ may also condense and provide a protective, less volatile overlayer, which is transparent at the wavelengths of the oxygen bands in the visible.

4. Conclusion

We studied gas trapping in water ice and optical properties of condensed films of pure oxygen and oxygen:water mixtures between 22 and 160 K. We find that millimeter thick water:oxygen ice is highly transparent, whereas pure oxygen films scatter light relatively strongly. Oxygen diffuses out of bubbles in vapor deposited ice, even at 25 K. The optical absorption bands of condensed oxygen in the visible shift to larger wavelengths with increasing temperatures. The bands disappear in tens of minutes at 160 K below our detectability limit. The results show that some condensed oxygen source at temperatures lower than Ganymede’s average temperatures must be responsible for the oxygen signatures observed in the satellite. This condensed oxygen can form in patches that are very cold because of a high albedo or because they have cracks or crevices or other areas that are in the shadow part of the day. The mass transport between relatively warm and cold places should produce an oxygen atmosphere that varies locally. Due to the exponential evaporation rates, the local atmosphere should be sensitive to small temperature changes and therefore to factors that include, inter alia, the type of terrain, orbital position, and distance to the Sun. This local atmosphere could be mapped with occultation experiments.

The analysis shows that there are multiple gaps in the current understanding of the question of oxygen in Ganymede. Discrepancies arise because the surface of the satellite is heterogeneous on the resolution scale of the optical probes that have been used so far. There is still no complete agreement between band positions and relative band intensities measured at Ganymede with those measured in the laboratory. The sensitivity of the oxygen band shapes to temperature and the environment suggests that significant advances in the understanding of this problem will result once higher resolution spectral mapping of oxygen on Ganymede becomes available.

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