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CONDENSED O_2 ON EUROPA AND CALLISTO

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ABSTRACT

High signal-to-noise ratio spectra of Europa and Callisto's trailing side show a 0.3% deep 5771 Å absorption band due to condensed O_2 at the same wavelength as a stronger band previously identified on Ganymede. Excellent longitudinal coverage for Europa shows that unlike Ganymede, where the band is much stronger on the trailing side, Europa shows no significant longitudinal variation in the O_2 band strength.

Key words: planets and satellites: general — planets and satellites: individual (Callisto, Europa) — techniques: spectroscopic

1. INTRODUCTION

In recent years, spectroscopy of the surfaces on the icy Galilean satellites has revealed the presence of several species other than water ice. O_2 (Spencer, Calvin, & Person 1995; Calvin, Johnson, & Spencer 1996) and O_3 (Noll et al. 1996) have been identified on the trailing side of Ganymede, as well as SO_2 on the trailing side of Europa (Lane, Nelson, & Matson 1981; Noll, Weaver, & Gonella 1995) and the leading side of Callisto (Noll et al. 1997). The *Galileo* near-infrared mapping spectrometer has seen CO_2 and possible S—H, C—N, and C—H features on Callisto and Ganymede (McCord et al. 1998), hydrated salts or sulfuric acid on Europa (McCord et al. 1999; Carlson, Johnson, & Anderson 1999b), and H_2O_2 on Europa (Carlson et al. 1999a).

The presence of condensed O_2 on Ganymede is inferred from a pair of weak (<2% deep) absorption bands at 5770 and 6275 Å, which require the absorption of a photon by two adjacent O_2 molecules and so are produced only in high-density condensed O_2. The high vapor pressure of condensed O_2 at Ganymede surface temperatures suggests that the O_2 is trapped in bubbles or crystal defects in a water ice matrix (Calvin et al. 1996; Johnson & Jesser 1997; Johnson 1999): the traps may themselves be produced by charged-particle irradiation. *Hubble Space Telescope* observations show that Ganymede's O_2 is concentrated at low latitudes (Calvin & Spencer 1997): the warmer temperatures at low latitudes may allow the coagulation and growth of radiation-triggered bubbles in the ice, providing sites for concentration of the O_2 (Johnson & Jesser 1997). Laboratory measurements of H_2O/O_2 ice mixtures have reproduced the O_2 absorption bands seen on Ganymede (Vidal et al. 1997; Baragiola & Bahr 1998), but in experiments so far the O_2 is gradually lost at temperatures above 70 K, leading to the more radical suggestion that the O_2 is exposed on the surface in small frost patches with daytime temperatures below 70 K, perhaps due to extremely high albedo, or even in an atmospheric haze (Baragiola & Bahr 1998; Baragiola et al. 1999; Bahr et al. 2001).

While it might be thought that Ganymede's intrinsic magnetic field (Kivelson et al. 1996) would protect the surface from bombardment by the low-energy particles (ion speed < co-rotation speed) that could produce the observed strong trailing-side concentration of O_2 on Ganymede, sufficiently low energy particles (<20 keV for protons) may be able to penetrate the field on the trailing side because of $\vec{E} \times \vec{B}$ drift associated with the co-rotational electric field of Jupiter's magnetosphere (Cooper et al. 2001). Magnetospheric particles might also be expected to produce an abundance of O_2 on Europa's trailing side, but earlier studies (Spencer et al. 1995) did not show an O_2 band on Europa.

2. OBSERVATIONS AND DATA REDUCTION

We obtained new CCD spectra of the Galilean satellites with the Ohio State University CCD spectrograph at the Lowell Observatory Perkins 72 inch (1.8 m) telescope in 1997 June and November, using similar observational and reduction techniques to those used previously (Spencer et al. 1995), with the difference that in the new observations we used an off-axis autoguider to track a nearby guide star, providing more consistent centering of the satellite in the spectrograph slit. Typical total integration time per satellite per night was about 300 s. Observations are logged in Table 1. Various gratings and slit widths were used, giving variable spectral resolution.

We concentrated on the 5770 Å rather than the 6275 Å band, because the latter is weaker and broader and also overlaps a sharp telluric 6280 Å CO_2 band and is thus harder to study from the Earth's surface. To remove Fraunhofer lines as precisely as possible, we took the ratio of the icy-satellite spectra to Io spectra taken the same night, rather than to a solar-type standard star. We chose Io because its ice-free surface composition made it less likely to have surface O_2 than the icy satellites. Taking the ratio to Io introduced a strong curvature in the spectra due to Io's very different continuum shape: this was removed by dividing by a cubic polynomial fit to the spectrum, excluding the 5875–5910 Å region where sodium emission from Io was prominent in the ratios.

We did not correct for wavelength-dependent atmospheric extinction, but the air-mass difference between the Io and icy-satellite spectra was generally less than 0.04 (Table 1). Ratios of the same satellite at different air masses show negligible telluric absorptions in the 5700–

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TABLE 1

LOG OF OBSERVATIONS

Date	Europa Mean Air Mass	Io Mean Air Mass	Callisto Mean Air Mass	Spectral Resn. (Å)	Europa CML[a]	Callisto CML[a]
1997 Jun 17	1.62	1.61	1.56	3	129	258
1997 Jun 18	1.73	1.63	...	3	226	...
1997 Jun 19	1.56	1.57	...	6	332	...
1997 Jun 20	1.56	1.56	...	6	74	...
1997 Jun 21	1.68	1.64	...	6	170	...
1997 Jun 22	1.56	1.57	...	6	277	...
1997 Jun 23	1.68	1.64	...	6	12	...
1997 Nov 2.......	1.66	1.70	...	20	50	...

NOTE.—Spectral resolution is defined as the FWHM of an unresolved spectral line.

[a] Central meridian longitude.

5900 Å region and placed an upper limit of 0.05% on the strength of any atmospheric features due to atmospheric extinction resulting from a 0.04 air-mass difference. We calibrated wavelengths by comparing Fraunhofer line positions with a solar spectrum (A'Hearn, Ohlmacher, & Schleicher 1983) before taking the ratio; estimated wavelength uncertainty is 1 Å.

3. RESULTS

The ratio spectra generally contain artifacts larger than the noise at some wavelengths, because of imperfectly canceled Fraunhofer lines, telluric features, or other effects. However, the improved observations and analysis reveal a previously unseen weak 5770 Å O_2 band in the Europa/Io and Callisto/Io ratios (Fig. 1). Though the individual spectra are noisy, all spectra show a consistent drop in reflectance between 5805 and 5770 Å, as expected from O_2 absorption. The shape of the absorption band on Europa is more apparent when all Europa/Io ratio spectra are averaged (Fig. 2). The band seems to have identical shape to that on Ganymede and is seen with similar strength on the leading and trailing sides. The single Callisto spectrum, also shown on Figure 2, has unexplained features that may be artifacts centered at 5550 Å. The Callisto O_2 band is not much stronger than these unexplained features, but its perfect wavelength match to the Europa and Ganymede features provides good evidence that it is a real feature.

The depth of such broad shallow bands, after taking the ratio to Io's complexly curved continuum, is difficult to measure precisely. In Figure 2 the 5630–5810 Å region of the O_2 absorption is excluded from the cubic fit so that the fit does not decrease the band depth, at the risk of introducing artifacts due to treating the region of interest differently from its surroundings. Band depth is 0.30% for the average Europa spectrum, 0.34% for the leading side, and 0.24% for the trailing side: the leading vs. trailing difference is probably not significant. Depth is 0.33% in the single Callisto spectrum, which covers Callisto's trailing hemisphere. For comparison, the maximum depth of the O_2 band on Ganymede's trailing side (Spencer et al. 1995; Fig. 2) is 1.8%, though as this depth was obtained from a Ganymede/Callisto ratio spectrum the true band depth on Ganymede may be slightly higher if the Callisto spectrum also contained O_2. The absorption minimum is at 5771 ± 1 Å, consistent with the 5773 ± 1 Å reported previously for Ganymede (Spencer et al. 1995).

4. DISCUSSION

The O_2 band was not seen in previous reductions of Europa spectra (e.g., Fig. 7 of Spencer et al. 1995), probably because the ratios of all spectra were taken with respect to Callisto rather than Io. Europa and Callisto (at the one longitude observed so far) apparently have very similar O_2 absorption band strength, so the band disappears in Europa/Callisto ratios. The similar O_2 bands on Europa and Callisto, despite their very different mean surface compositions, might lead to suspicion that the band is an artifact, perhaps due to a feature in Io's spectrum. However, we consider this unlikely. If the feature were on Io, it would have to be a reflectance excess with the same shape and

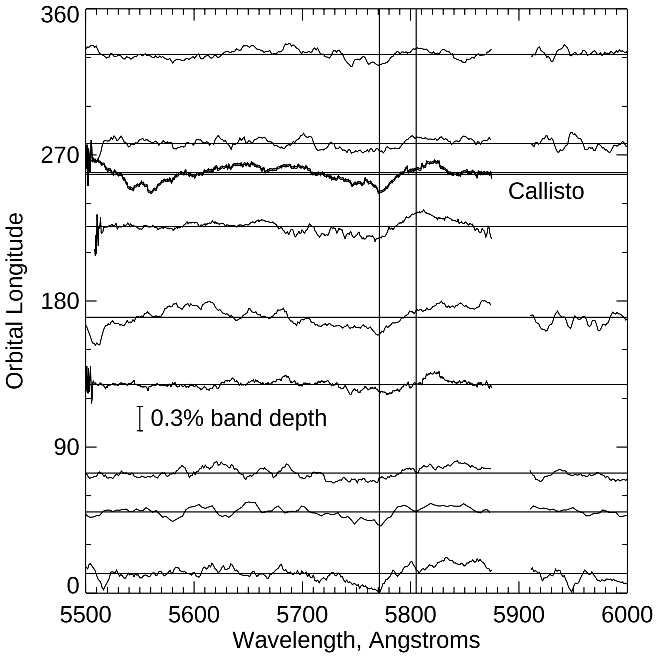

FIG. 1.—Spectra of Europa (*single unlabeled lines*) and Callisto (*double labeled line*), divided by contemporaneous Io spectra to remove Fraunhofer lines, arranged according to the central longitude of Europa or Callisto at the time of the observation and showing the band depth scale. Spectra are divided by a cubic fit (*horizontal lines*) to correct for the large difference in continuum shape between Io and Ganymede (Spencer, Calvin, & Person 1995). Sodium emission from Io, which appears as a negative feature at 5893 Å, has been cropped out of the spectra. A weak 5770 Å absorption band due to O_2 is seen in all spectra as a drop in the relative reflectance between 5805 and 5771 Å (*vertical lines*).

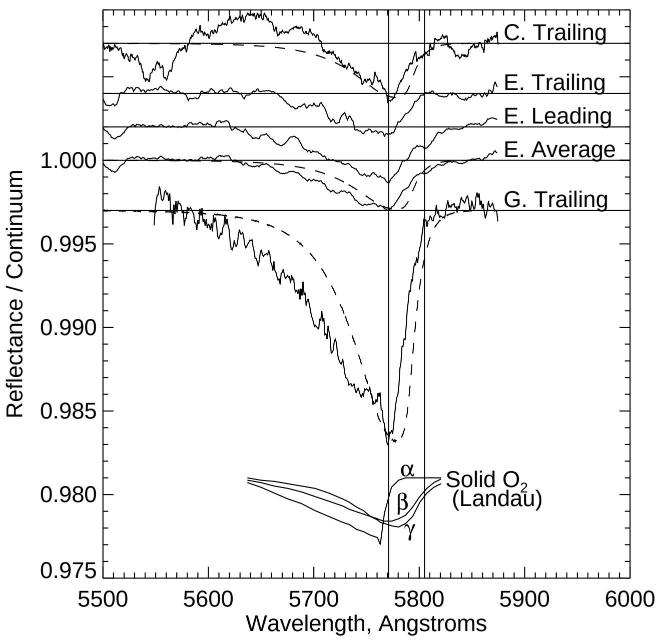

FIG. 2.—Averages of all Europa/Io ratios from Fig. 1 and separate averages of Europa's leading and trailing hemispheres (*E*), showing the weak O_2 band. Our single Callisto/Io ratio, from Fig. 1 (*C*) and a Ganymede trailing hemisphere/Callisto ratio from 1994 April 5 (*G*) has been taken, from Spencer et al. (1995), are also shown for comparison, as are transmission spectra for γ-phase O_2 with path lengths of 21, 19, and 90 μm, from Calvin, Anicich, & Brown (2002), matched to Callisto, Europa, and Ganymede, respectively. Unlike Fig. 1, the spectra are normalized to a cubic fit that excludes the 5630–5810 Å region of the O_2 band to allow more accurate measurement of the band depth. Finally we show laboratory spectra of all three phases of solid O_2, with arbitrarily vertical scaling, from Landau, Allin, & Welsh (1962). All spectra are offset vertically for clarity. For comparison with Europa and Callisto, vertical lines show the wavelengths of minimum reflectance (5771 Å) and return to continuum (5805 Å) of the Ganymede O_2 feature.

wavelength dependence as the indubitably real Ganymede O_2 absorption, but of opposite sign, and this seems highly unlikely. No instrumental artifact should appear only in Europa and Callisto spectra, but not in concurrent Io spectra (Io does have a smaller mean distance from Jupiter and thus more potential for artifacts due to Jupiter light contamination, but on several dates Europa was at a similar or smaller distance to Jupiter than was Io). We thus consider the only plausible explanation of the data, however surprising, to be that a weak O_2 band is present at similar strength, 0.3%, at all longitudes on Europa and at least one longitude on Callisto.

O_2 abundance is difficult to constrain from these observations, as the intrinsic strength of 5770 Å band is a very strong function of density of the O_2, which is unknown. On Ganymede we estimated a maximum absorption path length of 3 μm if the band was as strong as that of solid αO_2 as reported by Landau, Allin, & Welsh (1962; Spencer et al. 1995). In Figure 2 we use new measurements of the strength of the 5770 Å band in γO_2 by Calvin, Anicich, & Brown (2002) to match the observed band depths on Callisto, Ganymede, and Europa. The band is several times weaker in γ-phase O_2 than in the α-phase. If γ-phase band strengths were appropriate for the Galilean satellite O_2, path lengths of roughly 21 μm on Callisto, 19 μm on Europa, and 90 μm on Ganymede's trailing side would be implied, though it can be seen from Figure 2 that γ-phase O_2 does not match the band shape precisely. Translation from path length to absolute abundance then requires knowledge of the typical visible wavelength photon path length in the H_2O matrix (if the O_2 is dispersed in H_2O ice), and it is thus even more uncertain.

The presence of condensed high-density O_2 on Europa and Callisto constrains hypotheses for its formation on all the icy satellites, though we leave detailed exploration of these constraints to future papers. The presence of O_2 at all longitudes on Europa in similar amounts, in contrast to Ganymede, suggests that it is not generated by low-energy plasma bombardment, which occurs on Europa, because of the lack of a deflecting magnetic field, and strongly favors the trailing hemisphere. The idea that O_2 might be formed at all longitudes on Ganymede but destroyed or buried by micrometeorite bombardment on the leading side (Calvin & Spencer 1997) is also challenging to reconcile with the lack of an obvious leading vs. trailing asymmetry on Europa, which will have an even greater leading vs. trailing bombardment asymmetry because of its greater orbital speed. The reduced abundance of O_2 on Europa and Callisto compared with Ganymede also requires explanation: possible explanations for Europa might include scavenging of the oxygen by sulfur, which is probably more abundant on Europa's surface than on Ganymede's (Carlson et al. 1999b), or surface erosion by charged particle bombardment. For Callisto, the lower surface ice abundance than on Ganymede is likely to be part of the explanation for the lower O_2 abundance.

The observations confirm the highly oxidizing nature of Europa's surface inferred from the earlier detection of H_2O_2 and possible H_2SO_4. If these oxidants can be transported from the surface to the interior, they could conceivably provide an energy source for possible Europan organisms (Chyba 2000).

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