

# EUROPA'S TENUOUS ATMOSPHERE AND ITS INTERACTION WITH EUROPA'S POROUS SURFACE

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## Abstract

During my 2006-2007 VSGC fellowship I modeled the O<sub>2</sub> atmosphere of Jupiter's moon Europa. By assuming that atmospheric O<sub>2</sub> can react with species contained in portions of Europa's surface, my coauthors and I have been able to reproduce the O<sub>2</sub> density variations seen by a previously-unexplained HST observation. This work included further refinements to a regolith model that I published previous to the fellowship. Ongoing work is focused on modeling other atmospheric constituents to analyze recent Europa observations by the New Horizons spacecraft and in preparation for a possible future Europa mission, along with continued work on the O<sub>2</sub> model and its implications for the evolution of Europa's surface. The talk will include a brief introduction to tenuous atmospheres throughout the solar system.

## Introduction

The main focus of my research since commencement of the 2006 VSGC fellowship has been Europa's O<sub>2</sub> atmosphere. An interesting aspect of this problem was mentioned in McGrath et al. (2004), which showed a 2000 observation by the Hubble Space Telescope (HST). The observation showed a UV emission (an aurora) from Europa's O<sub>2</sub> atmosphere which suggests that the O<sub>2</sub> atmosphere is spatially non-uniform (Fig. 1). I recently submitted a paper to the journal *Icarus* with 4 coauthors that explains, with caveats, this strange phenomenon. The results of this research will help to interpret data from the New Horizons probe, observed Europa with its ultraviolet spectrometer, Alice, during the recent Jupiter flyby.

## Summary of the Atmospheric Model and its Results

Europa's O<sub>2</sub> atmosphere was predicted to exist by my university

advisor (Johnson et al., 1982) and was detected by the HST (Hall et al., 1995 and 1998). The O<sub>2</sub> is created by intense radiation from Jupiter's magnetosphere in a process called radiolysis. Energetic ions and electrons break up H<sub>2</sub>O molecules in Europa's surface, and some of the dissociation products form O<sub>2</sub>. The Ion radiation also ejects the O<sub>2</sub> (along with everything else in the surface) in a process called sputtering. This ejected O<sub>2</sub>, traveling on ballistic arcs, forms the tenuous "atmosphere." The atmosphere is detected via a distinct UV emission resulting from magnetospheric electron-O<sub>2</sub> collisions.

The spatially non-uniform O<sub>2</sub> UV emission was discovered by an HST observation in 2000, with a replacement instrument, the Space Telescope Imaging Spectrograph, which provided much higher spatial resolution than previous observations. Fig. 1 shows this observation along with a visible-light view of roughly the same portion of the disk. It is clear that there is a rough correlation between visibly bright terrain and O<sub>2</sub> UV emission. Europa's color

differences have been ascribed to differences in composition (e.g., Domingue and Hapke, 1992; Fanale et al., 1999), with bright terrain being relatively pure ice and dark terrain containing a variety of sulfur and, to a lesser extent, carbon compounds. Since  $O_2$  is known to react with such compounds, that correlation led me to

explore the possibility that  $O_2$ /surface reactivity is responsible for the spatial non-uniformity seen in the  $O_2$  UV emission. Specific chemical reactions were never specified, rather, I set out to see what reactivity could reproduce the HST observation (see also: Hand et al., 2006).

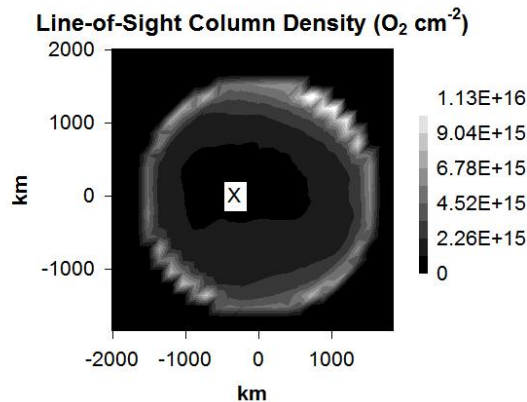
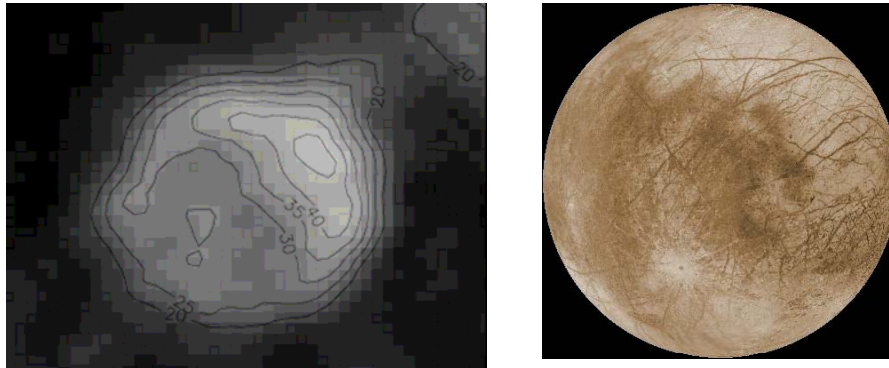


Figure 1. *Top left:* 2000 HST observation of UV emission from Europa's  $O_2$  atmosphere. Contours show  $O_2$  column density in units of  $10^{14} \text{ cm}^{-2}$ . *Top right:* visible view for roughly the same geometry. *Bottom center:* successful simulation of the  $O_2$  atmosphere, the arrow shows the trailing hemisphere apex.

I built a Monte-Carlo computer model of Europa's  $O_2$  atmosphere to test this hypothesis. The program follows test particles (each of which represents a large number of  $O_2$  molecules) on

ballistic trajectories. A trajectory begins with the launch of a test particle from a randomly-chosen location and with a randomly-chosen energy (using the appropriate probability distributions).

The ballistic trajectory is then calculated, and most O<sub>2</sub> return to the surface. Upon returning to the surface the O<sub>2</sub> can react, and thus disappear from the atmosphere, or, as appropriate for Europa's surface temperature, the O<sub>2</sub> desorbs and undergoes another ballistic arc.

Based on these trajectories and the assumption that the atmosphere is in steady state (i.e., the density is unchanging), the program calculates densities and column densities such as the result in Fig. 1. The model relies on assumptions based on observations, laboratory results, and previous atmospheric models. For instance, Europa's atmosphere is assumed to be collisionally thin, so that collisions between atmospheric particles can be neglected to first order (Shematovich et al., 2005). I further assumed that the O<sub>2</sub> line-of-sight column density is proportional to the O<sub>2</sub> UV airglow, an assumption that depends on the electron environment near Europa. This assumption is roughly valid for the hemisphere I modeled, the trailing hemisphere, but may be inappropriate for the leading hemisphere (Saur and Strobel, 1998), and, in any case, will require further study. This is a difficult problem to address fully, as it would also require a plasma simulation.

To get the result seen in Fig. 1 required experimentation with two settings: the spatial distribution of O<sub>2</sub> ejection and the spatial distribution of O<sub>2</sub>/surface reactivity. The spatial distribution of O<sub>2</sub> ejection was uncertain. Previous models have proposed a variety of ejection distributions. Those distributions ranged from a predominantly trailing hemisphere source (Ip et al., 1998) to a nearly uniform source (Paranicas et al., 2002). I experimented with these and an

additional case in which O<sub>2</sub> is preferentially ejected from the bright icy regions.

The reactivity is given by a quantity  $R_{\text{eff}}$ , which is the probability that an O<sub>2</sub> molecule encountering the surface will react (the subscript is explained in the next section). The spatial variation in  $R_{\text{eff}}$  is based on the surface albedo; specifically, I used a global map from McEwen (1986), who categorized the surface into 4 regions of varying darkness. I assigned the darkest region a reactivity  $R_{1,\text{eff}}$ , gave the brightest region a reactivity of zero, and gave the other two regions intermediate values. The reactivity distribution was thus parameterized by the value  $R_{1,\text{eff}}$ .

For each ejection spatial distribution, I found the  $R_{1,\text{eff}}$  that best matched the 2000 HST observation. I found that values of  $R_{1,\text{eff}} = 0.01$  to  $0.025$  were needed. An example of the results is shown in Fig. 1. For one of the spatial distributions I found that no reactivity can reproduce the observation. Once I found that the column density spatial variation roughly matched the HST observation, I then calculated the total O<sub>2</sub> source rate required to reproduce the column observed (the program only outputs the column density variation, as I input the O<sub>2</sub> ejection distribution, but not the O<sub>2</sub> source rate). I found that the O<sub>2</sub> source rate required was about an order of magnitude larger than most previous estimates. One of my coauthors, though, previously estimated a similar value using a different approach (Cooper et al., 2001), and previous atmospheric modelers had explored the possibility of such a high source rate.

## Regolith and Reactivity

For the O<sub>2</sub> atmosphere model I used a probability  $R_{\text{eff}}$  to represent the surface/O<sub>2</sub> reactivity. Since Europa's surface is covered by a porous regolith (Domingue and Verbiscer, 1997), this reaction probability actually represents the cumulative probability of many O<sub>2</sub>/surface interactions. Using a Monte Carlo model of radiation-regolith interactions developed for a previous paper (Cassidy and Johnson, 2005), I found a simple relationship between these two probabilities. That relationship, found by a fit to the Monte Carlo results, is given by

$$R_{\text{eff}} = R^{1/3} \quad 0.01 \leq R \leq 1$$

$$R_{\text{eff}} = R^{0.4} \quad R \leq 0.01$$

where  $R$  is the probability of reaction for a single O<sub>2</sub>/surface interaction and  $R_{\text{eff}}$  is the enhanced probability of reaction in a regolith. For small  $R$ , this results in substantial reactivity enhancement. For instance, the  $R_{\text{eff}}=0.01$  means that an O<sub>2</sub> molecule returning to the surface after a ballistic arc has a probability of 0.01 of reacting in the regolith. The corresponding probability  $R=1.0 \times 10^{-5}$ ; an O<sub>2</sub> molecule in that model has to interact, on average, with  $10^5$  surfaces before reacting.

This result does not depend on specific properties of O<sub>2</sub> or the European regolith, except that the regolith needs to be highly porous. Further, the result is remarkably insensitive to program parameters, such as particle incidence angle and regolith grain shape. Specifically, the Monte Carlo program was designed with the assumption that the mean free path is larger than the average grain width  $D$ . This results in the criterion that the regolith must have a volume fraction of empty space (porosity) greater than 1/3. This forgiving criterion thus includes most, if

not all, airless surfaces in the Solar System.

## Ongoing Work

The parameters for the O<sub>2</sub> atmosphere model were set in order to reproduce a single HST image, but, since we made use of a global map, it also provides predictions for other viewing geometries. These predictions will be tested by data from the New Horizons mission to Pluto, which recently encountered Jupiter.

A spaceprobe orbiting Jupiter's moon Europa, of the sort considered by both ESA and NASA, would provide an opportunity to determine the composition and morphology of atmospheric components besides O<sub>2</sub>. Many other species are expected, but only Na and K have been observed. The detection of other species would require in-situ observation of the atmosphere with a mass spectrometer, either with or without the ability to detect neutrals (Johnson et al., 1998). This in turn could answer questions about the surface composition and, possibly, aspects of the composition of Europa's ocean that would otherwise require a much more expensive landing mission. Its atmosphere is thought to be primarily produced by sputtering and radiation-induced decomposition of surface material by energetic ions and electrons from Jupiter's magnetosphere. The primary surface ejecta is H<sub>2</sub>O, of which 100s of molecules are ejected per incident ion by the impacting energetic oxygen and sulfur ions (Johnson, 1990). Because these yields are large, other species present in the ice can be carried into the atmosphere along with the H<sub>2</sub>O (such as happens with O<sub>2</sub>).

Using that principle I have been able to simulate another component of Europa's aurora, shown in Fig. 2. These images, captured by Cassini's Imaging Science Subsystem Narrow Angle Camera, show Europa in eclipse. A feature on the upper-left portion of the disk is emission from the spectral range of 200-1050 nm (Online Supplement from Porco et al., 2003). This range does not include the O<sub>2</sub> emissions discussed above. I have found that the spatial non-uniformity can be reproduced if the atmospheric component, whatever it may be, is ejected preferentially from the trailing hemisphere dark terrain. Na is the most likely candidate: the dark material is thought by some to contain large

amounts of Na, and the observed brightness can be roughly reproduced by estimated values for the total Na source rate and electron-impact excitation rate (the source rate has been previously inferred from observations of Europa in sunlight from Earth-based telescopes; see, e.g., Leblanc et al., 2005).

In addition, as at Enceladus, Europa may be outgassing; but, unlike Enceladus, Europa has a considerable gravitational field so that the vented gas would mostly return to the surface. Detecting the composition and spatial distribution of the ejected or vented molecules could provide insight into the composition of Europa's surface and, possibly, of its putative subsurface ocean.

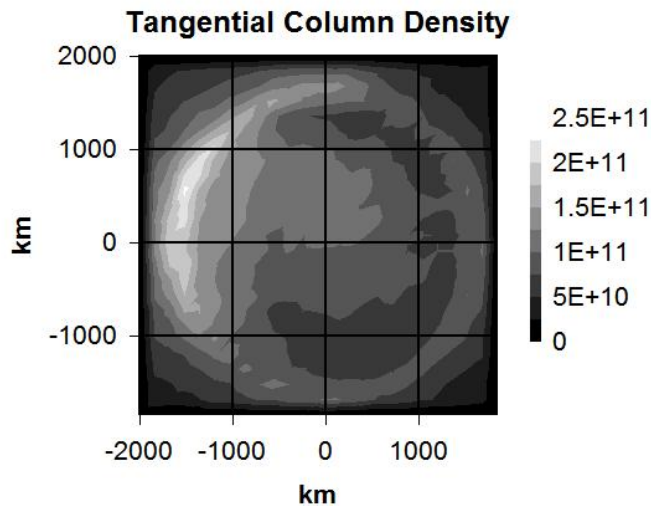
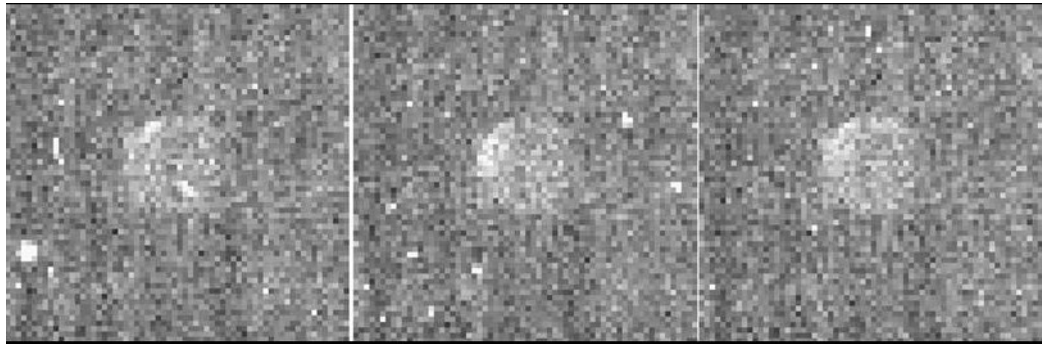


Figure 2. *Top*: Cassini ISS observation of “visible” emission from Europa seen during eclipse. *Bottom*: Simulation of Na column density ( $\text{cm}^{-2}$ ) seen from the same angle as the observation.

An outstanding question which could be resolved by measurements from an orbiting mass spectrometer is the identity of the hydrated sulfates seen all over Europa. These sulfates have been shown to have their highest concentrations on the trailing hemisphere and along linear tectonic features (Fanale et al., 1999). Their infrared spectrum has been suggested to be consistent with both ocean-derived sulfate salts and sulfuric acid produced by radiation-altered, plasma-injected sulfur (Orlando et al., 2005). Since the

suggested salts are very different, determining the spatial distribution and composition of the ejecta can be used to determine the importance of space and ocean sources of sulfur. The results in Fig. 2, for instance, suggest that the unknown hydrate is, at least partially, a Na salt. I will use proposed maps of surface composition to estimate the density of these species above Europa’s surface. The results from such simulations can then be used to determine the required sensitivity for a mass spectrometer on an orbiting probe.

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