

First Annual Report for NASA Contract NASW 02-037,
“Radiolytic Model for Chemical Composition
of Europa’s Atmosphere and Surface”,
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1. SUMMARY

The overall objective of the present effort is to produce models for major and selected minor components of Europa's neutral atmosphere in 1-D versus altitude and in 2-D versus altitude and longitude or latitude. A 3-D model versus all three coordinates (alt, long, lat) will be studied but development on this is at present limited by computing facilities available to the investigation team. In this first year we have focused on 1-D modeling with Co-I Valery Shematovich's Direct Simulation Monte Carlo (DSMC) code for water group species (H_2O , O_2 , O , OH) and on 2-D with Co-I Mau Wong's version of a similar code for O_2 , O , CO , CO_2 , and Na . Surface source rates of H_2O and O_2 from sputtering and radiolysis are used in the 1-D model, while observations for CO_2 at the Europa surface and Na detected in a neutral cloud ejected from Europa are used, along with the O_2 sputtering rate, to constrain source rates in the 2-D version. With these separate approaches we are investigating a range of processes important to eventual implementation of a comprehensive 3-D atmospheric model which could be used to understand present observations and develop science requirements for future observations, e.g. from Earth and in Europa orbit. Within the second year we expect to merge the full water group calculations into the 2-D version of the DSMC code which can then be extended to 3-D, pending availability of computing resources. Another important goal in the second year would be the inclusion of sulfur and its more volatile oxides (SO , SO_2).

Already we are looking ahead beyond the present contract scope on Europa to development of neutral atmosphere models for Ganymede and Callisto, and of ionospheric models for all three icy Galilean moons. Since the dominant loss process for atmospheric neutrals at Europa is found in our work to be ionization, the loss rate distributions for the neutral model become the source rate distributions for a future ionospheric model. At larger scales the neutrals and ions lost from Europa contribute to the magnetospheric environment of Jupiter, forming the Europa neutral torus detected (Mauk et al., 2003a) by Cassini Orbiter's Dec. 2000 flyby of Jupiter and mixing into the magnetospheric composition with other sources from the Io plasma torus, Jupiter's upper atmosphere, and solar wind plasma flowing into Jupiter's outer magnetosphere from interplanetary space.

Measurements of elemental and isotopic composition for ions and neutrals in the Jovian magnetosphere and near the moons would be important goals for the planned Jupiter Icy Moons Orbiter (JIMO) mission. The PI has participated in definition of scientific measurement objectives for JIMO as a member of the Science Definition Team, which has now issued its full report (Greeley et al., 2004). The present contract work on neutral atmospheric modeling for Europa, and envisaged extensions for the other moons and for ionospheres, have contributed to two additional proposals (see Sect. 4.3) submitted for team participation as Co-Is to the JIMO-related High Capability Instruments for Planetary Exploration (HCIPE) program. The atmospheric and ionospheric models would substantially contribute to development of measurement requirements for the proposed radio plasma (Green et al., 2003b) and low-energy neutral atom imaging instruments, as well as being important for planning of the JIMO orbital operations around the icy moons.

The many presentations and publications on contract-related topics by investigation team members are listed in Section 4, and some of the abstracts for presentations are given in Section 3. A major achieved milestone for the first year is completion of the water group modeling in 1-D and submission of a comprehensive publication (Shematovich et al., 2004) to Icarus. Some highlights of this paper, along with parallel results on the 2-D model, are discussed in the following section.

2. SURFACE-BOUND OXYGEN ATMOSPHERE OF EUROPA

Shematovich et al. (2004) describe results for a collisional DSMC model of Europa's atmosphere in which the sublimation and sputtering sources of H₂O molecules and their molecular fragments are fully accounted for, also including O₂ produced mostly by penetrating electrons in volume ice and sublimating out from the surface as cold gas at temperature ~ 100 K. Dissociation and ionization of H₂O and O₂ by magnetospheric electron, solar UV-photon and photo-electron impact, and collisional ejection from the atmosphere by the low energy plasma are taken into account. Adsorption of atmospheric species at the ice turns out to be critical for evolution of an atmosphere dominated by molecular oxygen. Among the water group species, only O₂ is assumed to circulate freely between the atmosphere and the presumably porous ice surface. Contributions of H₂O, O, and OH to total atmospheric density are very limited, since these stick to and/or recombine with surface ices on contact. For the electron impact ionization rates used, pick-up ionization is the dominant oxygen loss process. All ions produced in the model are assumed to be swept away in the corotating magnetic field. The present model includes no ion-neutral interactions in the atmosphere. Neutral oxygen is lost directly into the Europa torus at lower rates by photo-dissociation and atmospheric sputtering. Hydrogen atoms and molecules, e.g. from H₂O dissociation, rapidly escape from the atmospheric system into the neutral torus and are not followed after production. Since O₂ has a long residence time in the atmosphere, the oxygen source rate for the torus is lower than for hydrogen, making the latter the dominant species from the Europa source.

Observational constraints on the atmosphere are few, so we have made a variety of calculations in the 1-D case for different relative source rates of O₂ and H₂O at the Europa surface from sputtering and sublimation. Results for altitude profiles of number density and total escape flux for H₂O, O₂, and O from the so-called D, E, and F models are shown in Figure 1. OH profiles have also been calculated but are not shown. In all three cases the sputtering source flux for O₂ is taken as 2×10^9 O₂/cm²-s, and we assume that the H₂O source rate is 2×10^9 H₂O/cm²-s for (D) only sputtering, (E) sublimation at 100 K, and (F) equal contributions to the same total source flux from both sputtering and sublimation. The sputtering source flux is based on measurements of energetic heavy ion fluxes and calculated yields for sputtered H₂O from the work of Cooper et al. (2001). Yields for O₂ from laboratory measurements are variously found to be lower or comparable than for H₂O, and radiolytic chemistry from penetrating ion and electron interactions in the volume ice could boost the O₂ source. In all cases O₂ is the dominant density component below 200 km altitude, while O becomes dominant at higher altitudes in all models and dominates the oxygen escape fluxes in models D and E at all altitudes.

Figure 2 shows the energy distributions of upward fluxes from model D for O₂ and H₂O neutrals at the 100-km nominal altitude of a future orbiter such as JIMO. The

sputtering source distributions at the surface are overlaid for comparison. The relative rollover downward in 100-km O₂ flux, relative to source flux, with energy above the gravitational escape threshold arises from thermalization during many repeated contacts with the cold 100-K surface. In comparison, the H₂O fluxes at 100 km match the source fluxes well beyond the escape energy, so there is little spectral modification. For H₂O-like species, i.e. those that stick on return to the surface, this suggests that a low-energy neutral imaging instrument, as proposed for JIMO with our support by Collier et al. (2003), could directly map the composition of regions on the surface at horizontal resolution of tens of kilometers for species which are efficiently sputtered such as Na. This could be critical for resolution of questions on origins of observed sulfate salts, including that of Na₂SO₄, that show variations at this scale from near-infrared mapping.

For an O₂ - dominated atmosphere, a set of 2-D numerical runs was performed by Co-I Wong to study the distributions of O₂ and other minor species that are likely to exist in Europa's atmosphere. H₂O and its dissociation products were not included but will be in later phases. The same source rate as for the 1-D (D, E, F) models was used but with the addition of minor source components for CO₂ and Na at respective surface concentrations relative to H₂O of 1 and 3 % as inferred from Galileo Orbiter near-infrared observations. Only O and Na were assumed to stick on contact with the surface. The axis of symmetry of the 2-D model is aligned with the direction of the upstream plasma flow. A 'ram' angle theta is defined with a value of 0 degrees at the trailing hemisphere apex and 180 degrees at the leading apex. The O₂ source is assumed to decrease by a factor of 1.5 from the trailing to the leading apex based on earlier work of Pospieszalska and Johnson (1988). Total column densities for the source species and the products O and CO are shown in Figure 3 versus the theta angle. The O₂ profile at the column density observed by Hubble Space Telescope observations shows little variation with ram angle, since O₂ is highly mobile and frequently in contact with the 100-K surface. The higher CO₂ density at the leading apex reflects the observed source distribution, but CO is also highly mobile like O₂, and O is coupled to the local density for O₂. These runs confirmed the 1-D results that pickup ion production by electron-impact ionization with a lifetime for O₂ of 3.5×10^5 s is the primary atmospheric loss process and that a global source $\sim 1 \times 10^{25}$ /s of neutral oxygen is contributed to the Europa torus. The computed Na column density at high altitude is consistent with Earth-based observations of Europa's Na cloud.

References for Sections 1 and 2

- Collier, M. K., et al., "Remote Sensing the Jovian Plasma Environment Using Low Energy (10 eV-4 keV) Neutral Atom Imaging", proposal submitted to NRA-03-OSS-01-HCIPE, High Capability Instruments for Planetary Exploration, 2003.
- Cooper, J. F., R. E. Johnson, B. H. Mauk, H. B. Garrett, and N. Gehrels, Energetic Ion and Electron Irradiation of the Icy Galilean Satellites, *Icarus*, **149**, 133-159, 2001.
- Greeley, R., et al., Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO), Feb. 13, 2004.
- Pospieszalska, M. K., and R. E. Johnson, Magnetospheric ion bombardment profiles of satellites: Europa and Dione, *Icarus*, **78**, 1-13, 1989.
- Shematovich, V. I., R. E. Johnson, J. F. Cooper, and M. C. Wong, Surface-bounded atmosphere of Europa, submitted to *Icarus*, 2004.

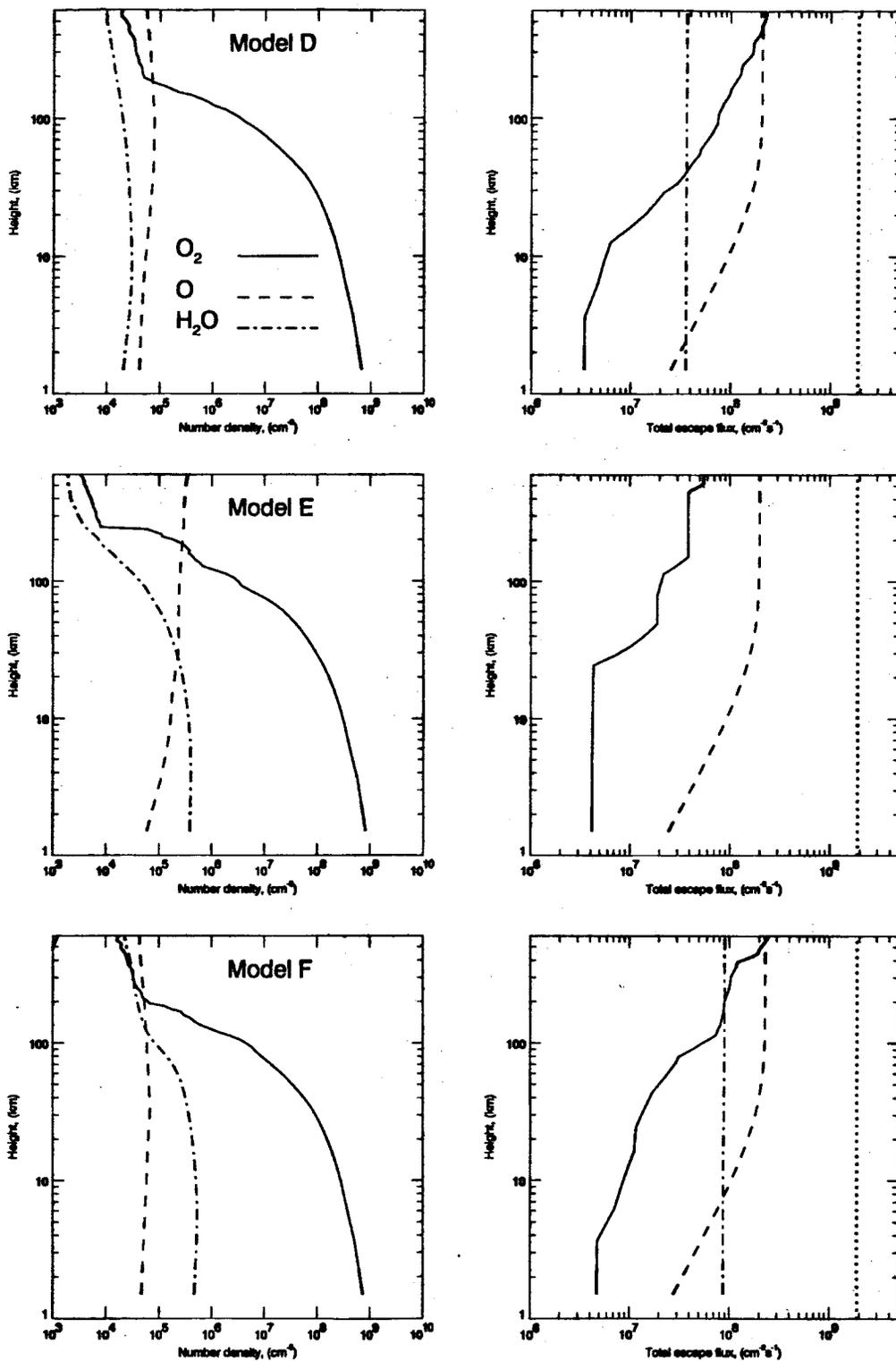


Figure 1. Height profiles of number densities (left panels) and total escape fluxes (right panels) of O₂ (solid line), H₂O (dot-dashed line), and O (dashed line) in the surface-bounded atmosphere of Europa for Models D (top panels), E (middle panels), and F (bottom panels). Dotted line in right hand panels is the O₂ source rate of 2×10^9 O₂/cm²-s common to all three models.

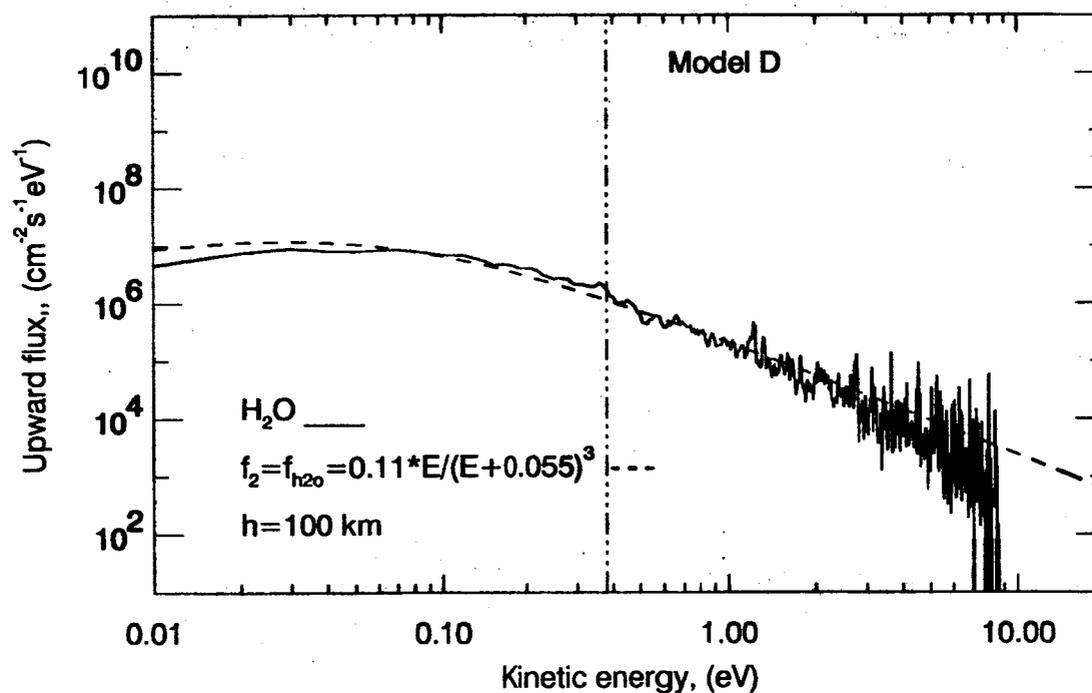
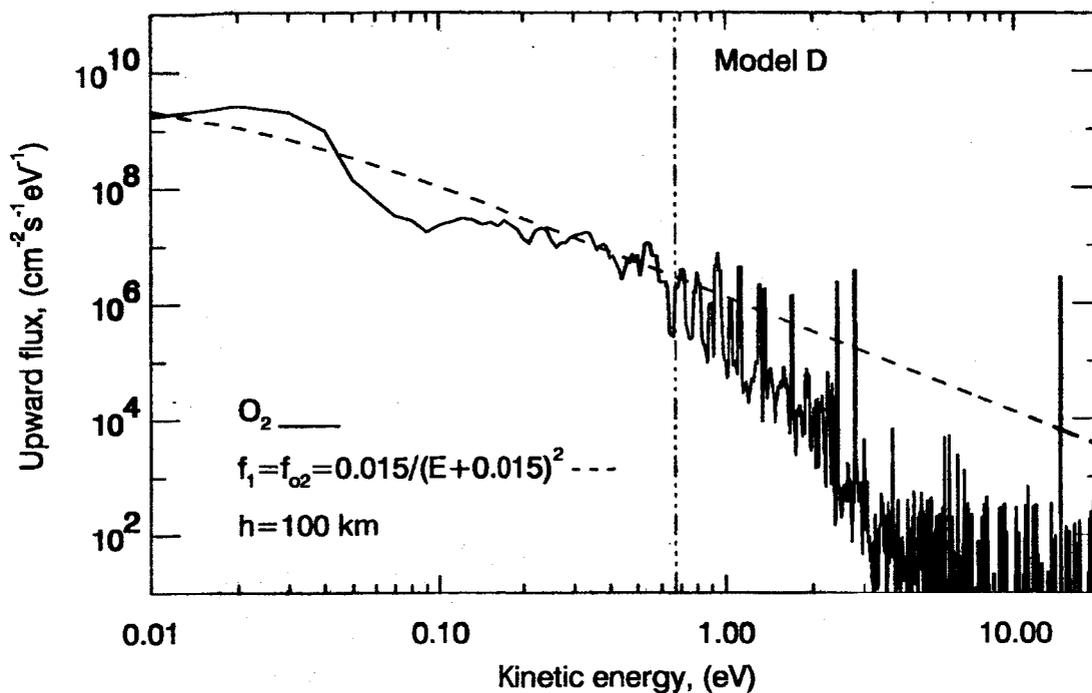


Figure 2. Energy spectra (solid lines) of upward fluxes of O_2 and H_2O in the near-surface region at height of 3.6 km for Model D. Energy spectra of surface sources are shown by dashed lines. Vertical dot-dot-dot-dashed lines at 0.38 eV and 0.67 eV show the escape energy of H_2O and O_2 molecules.

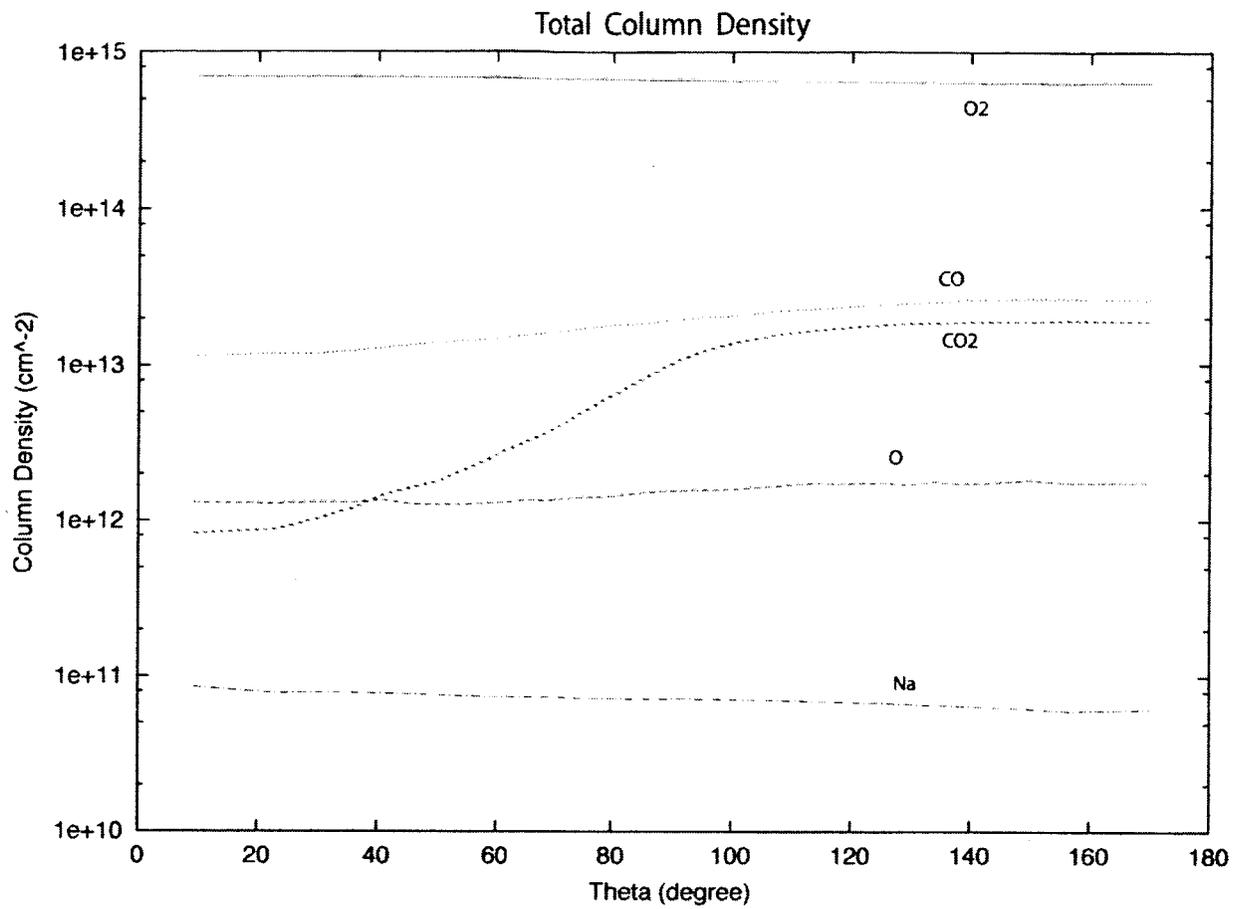


Figure 3. Total column density of species along the meridian plane from the trailing point ($\theta = 0$) to the leading point ($\theta = 180$). CO and O are primarily produced from the dissociation of CO_2 and O_2 , respectively. Because of its relatively long lifetime, CO is more abundant than CO_2 despite being the daughter species.

3. SELECTED ABSTRACTS FOR PRESENTATIONS

Khurana et al. (2003)

Field and Plasma Science with the Jupiter Icy Moons Orbiter (JIMO)

K. K. Khurana, W. S. Kurth, J. F. Cooper, J. H. Waite, J. E. Connerney, J. L. Green, F. Crary, W. R. Paterson, R. E. Johnson, C. Paranicas, and B. H. Mauk

The field and plasma investigations from JIMO would address fundamental science objectives related to chemistry, internal structure and evolution of Jupiter's Galilean icy satellites. In addition, data collected during the cruise phases of the mission would identify azimuthal asymmetries in the structure and dynamics of the Jovian magnetosphere. The Priority 1 objectives identified by the field and plasma subgroup assisting the JIMO SDT are: (1a) determine the presence and distribution of subsurface liquid water in the icy Galilean moons, (1b) determine the nature of satellite-magnetosphere interactions including the radiation environment of these moons, and (1c) determine the surface composition and properties of materials on these moons. The key investigations that reveal the presence and distribution of subsurface liquid water are low-frequency sub-surface sounding and the magnetic induction response of conducting oceans to the changing magnetic field in the rest frames of the moons. The magnetic field is also perturbed by the interaction of the moon with the Jovian plasma. Plasma observations and/or DC electric field measurements are therefore required to separate the internal and external sources of magnetic field perturbations. Further information on the thicknesses and properties of the moon ice crusts, and on the changing magnetic environments of the moons related to the induced fields, would be provided by a low frequency sub-surface sounder (working at kHz to MHz as compared to GHz used by ice penetrating radar). The surface composition objective can be addressed from in situ measurements of neutral or charged species in the moon atmospheres, ionospheres, dust clouds, and orbital gas tori, and by spectrographic imaging of neutral atoms and x-rays from the irradiated surfaces. The Priority 2 objectives are (2a) understanding the asymmetries in the structure and dynamics of Jovian Magnetosphere and (2b) understanding the deep internal structure of the icy Galilean moons. In the cruise phases of the mission, data collected from all local times at near-constant radial distance would help us determine local time asymmetries of the magnetosphere with an unprecedented accuracy. The internal structure objective can be addressed by inferring the magnetic induction response of the cores of the moons at very low frequencies. Electric field, plasma, energetic particle, and radio sounding measurements would further constrain the induction response. Since studies of Io are not a stated goal of JIMO mission, investigations of Io and its torus were assigned to Priority 3. Monitoring of the Io torus with ultraviolet auroral imaging and decametric radio emissions, and of Io's volcanism through imaging, would provide information about one of the principal sources of plasma and dynamics in the Jovian magnetosphere. We will also discuss how, in a conceivable extended phase of the mission, in-situ measurements near Io would shed light on the internal state and structure of this highly active moon and its interaction with the magnetospheric plasma.

Johnson et al. (2003d)

**Atmospheres Produced by Magnetospheric Irradiation
of Jupiter's Icy Galilean Moons**

R. E. Johnson, J. F. Cooper, V. I. Shematovich, R. W. Carlson,
M. C. Wong, F. Leblanc, and J. H. Waite

Sputtering by magnetospheric ions and radiolytic processes induced by the energy deposited by energetic ions and electrons [1] are sources of atmospheres and ionospheres of the icy Galilean satellites and are also significant drivers of molecular chemistry on their surfaces [2]. Ejection of neutrals from these surfaces and atmospheres and magnetic pickup of ions from the ionospheres are the source of material for a neutral torus and the Jovian magnetosphere at each of the satellite's orbital position. In-situ measurements of local magnetospheric, ionospheric, and atmospheric composition by the proposed Jupiter Icy Moons Orbiter (JIMO) will clearly also contribute our understanding of the evolution of the satellite surfaces [3]. In this paper the connection between radiolytic production of atmospheric ions and neutrals, and the composition of the moon surfaces, will be described. This is done in order to assess our ability to relate atmospheric and ionospheric composition measurements to a description of the surface composition [3]. The state of our understanding of the radiolytic production of volatiles and refractory species in these surfaces will be reviewed and the results of model atmosphere calculations [4,5] will be reviewed and new model calculations will be presented. Particular attention will be paid to important trace gas-phase molecules detected Europa, Ganymede or Callisto that might be indicative of material exchange between the irradiated surfaces and the putative sub-surface oceans. An important issue for astrobiology at Europa is the effect of the radiation environment and the highly oxidized surface chemistry on detection of any potential biochemical signatures of life or precursors transported to the sensible surface from an ocean. The model calculations of the icy satellite atmospheres will also be useful for planning of instruments for future missions such as JIMO. [1] Cooper, J.F., R.E. Johnson, B.H. Mauk, H.B. Garrett, and N. Gehrels 2001. Energetic Ion and Electron Irradiation of the Icy Galilean Satellites. *Icarus* 149(1), 133-159. [2] Johnson, R.E., R.W. Carlson, J.F. Cooper, C. Paranicas, M.H. Moore, and M. Wong 2003. Radiation Effects on the Surface of the Galilean Satellites, ed. F. Bagenal, *Jupiter: Planet, Satellites & Magnetosphere*, Cambridge University Press, Cambridge, in press. [3] Johnson, R.E., R.M. Killen, J.H. Waite, W.S. Lewis 1998. Europa's Surface and Sputter-Produced Ionosphere. *Geophys. Res. Letts.* 25, 3257-3260. [4] Shematovich, V.I. and R.E. Johnson 2001. Near-Surface Oxygen Atmosphere at Europa. *Adv. SpaceRes.* 27, 1881-1888. [5] Leblanc, F., R.E. Johnson and M.E. Brown 2002. Europa's Sodium Atmosphere: an Ocean Source? *Icarus* 159, 132-144.

**Supply of Trans-Europa Neutral Torus
by the Surface-bounded Atmosphere of Europa**

V. Shematovich, R. E. Johnson, J. F. Cooper, and M. C. Wong

Magnetospheric ion sputtering is an important source of neutrals at the icy Galilean satellites [1-3]. The Cassini Magnetosphere Imaging Instrument (MIMI) has detected [4] a neutral cloud located at Europa's orbit and likely consisting of sputtering products. A collisional Monte Carlo model of Europa's surface-bounded atmosphere in which the thermal and sputtering sources of H₂O molecules and their molecular fragments are accounted for was developed [5]. Dissociation and ionization of H₂O and O₂ by magnetospheric electrons, solar UV radiation and photoelectron impact, and collisional ejection from the atmosphere by the low energy plasma are taken into account. The surface-bounded O₂ atmosphere of Europa originates from a balance between radiolysis of the satellite icy surface by the solar UV radiation and high-energy magnetospheric plasma and the collisional ejection from the surface-bounded atmosphere by the low-energy plasma. The enhanced oxygen production rate found earlier [6] is used along with comparable H₂O ejection rate. Calculations show that the atmospheric chemical composition is determined by both the water and oxygen photochemistry in the near-surface atmospheric region, escape of suprathermal neutrals into the Jovian system, and the adsorption-desorption exchange by radiolytic water products with the satellite surface. It is shown, as was the case for the sodium atmosphere [7], that the oxygen and hydrogen loss from Europa's atmosphere supplies its gas torus [8]. The calculated oxygen supply rates are in the range $(6-10) \times 10^{27}$ atoms per second depending on the ratio of thermal (evaporation) and nonthermal (sputtering) source rates. Using an oxygen ionization rate of $2.0 \times 10^{-6} \text{ s}^{-1}$ the estimate of the total number N of neutrals in the torus is $(3.0 - 5.0) \times 10^{33}$ O atoms. This should be doubled to take into account the escape of atomic and molecular hydrogen. This estimate approaches that inferred from observations [4] $(4.5 - 9.0) \times 10^{33}$ atoms. Therefore, the collisional Monte Carlo model of Europa's surface-bounded atmosphere may be able to provide the required supply of neutrals to the trans-Europa gas torus in the inner Jupiter's magnetosphere. [1] Johnson, R.E., et al. 1998. Europa's Surface and Sputter-Produced Ionosphere. GRL 25, 3257-3260. [2] Cooper, J.F., et al. 2001. Energetic Ion and Electron Irradiation of the Icy Galilean Satellites. Icarus 149, 133-159. [3] Johnson, R.E., et al. 2003. Radiation Effects on the Surface of the Galilean Satellites, ed. F. Bagenal, Jupiter: Planet, Satellites & Magnetosphere, Cambridge University Press, Cambridge, in press. [4] Mauk B. H., et al. 2003. Energetic neutral atoms from a trans-Europa gas torus at Jupiter, Nature 421, 920-922. [5] Shematovich, V.I., R.E. Johnson, and J.F. Cooper 2003. Surface-bounded Oxygen Atmosphere of Europa. EGS-AGU-EGU Joint Assembly, abstract 13094, Nice, France. [6] Shematovich, V.I. and R.E. Johnson 2001. Near-Surface Oxygen Atmosphere at Europa. Adv. Space Res. 27, 1881-1888. [7] Leblanc, F., R.E. Johnson and M.E. Brown 2002. Europa's Sodium Atmosphere: an Ocean Source? Icarus 159, 132-144. [8] Eviatar, A., A. Bar-Nun, and M. Podolak 1985. European surface phenomena. Icarus 61, 185-191.

Green et al. (2003b)

Remote Radio Sounding Science For JIMO

J. L. Green, B. W. Reinisch, P. Song, S. F. Fung, R. F. Benson, W. W. Taylor,
J. F. Cooper, L. Garcia, T. Markus, D. Gallagher, and P. Gogineni

Radio sounding of the Earth's topside ionosphere and magnetosphere is a proven technique from geospace missions such as the International Satellites for Ionospheric Studies (ISIS) and the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE). Application of this technique to the Jupiter Icy Moons Orbiter (JIMO) mission will provide unique remote sensing observations of the plasma and magnetic field environments, and the subsurface structures of Europa, Ganymede, and Callisto. Spatial structures of ionospheric plasma above the surfaces of these bodies will vary in response to magnetic field perturbations from magnetospheric plasma flows, ionospheric currents from ionization of sputtered surface material, and induced electric currents in salty subsurface oceans. Radio sounding at 3 kHz to 10 MHz will provide globally-determined electron densities necessary for the extraction of the oceanic current signals and will supplement in-situ plasma and magnetic field measurements. Long-range magnetospheric sounding, pioneered by the radio plasma imager (RPI) instrument on IMAGE, has provided electron density distributions along magnetic field lines and in radial directions on time scales of minutes. RPI has also been able to measure the entire electron plasma density distributions (in the orbit plane) of the Earth's polar cap and the plasmasphere within one pass of the spacecraft. In a similar manner, a radio sounder orbiting an icy moon would be able to measure the electron density along the magnetic field into each hemisphere and provide information on the Jovian magnetospheric background, the magnetospheric influences on the moon's ionospheres, and distortions of magnetic field line geometry from model predictions. The higher-power source available from JIMO would allow radio sounding transmissions at much higher powers than those used on ISIS or IMAGE making subsurface sounding of the Jovian icy moons possible at frequencies above the ionosphere peak plasma frequency from ~5 MHz to 40 MHz. Subsurface variations in dielectric properties, can be investigated by radio sounding allowing the detection of dense and solid-liquid phase boundaries associated with oceans and related structures in overlying ice crusts.

Cooper (2003e)

Energetic Particles as Probes of Magnetic Environments for Galilean Moons at Jupiter

J. F. Cooper

Perhaps the most exciting discovery from Galileo Orbiter multiple flybys of Galilean moons has been presence of permanent (Ganymede) and induced (Europa, Ganymede, and Callisto) dipole moments from magnetometer data. Two polar flybys of Io ruled out a permanent dipole but the complex plasma environment has made determinations for an induced dipole, e.g. from a magma ocean, more elusive. However, a magnetometer can only measure local field vectors and magnitude at the spacecraft, not global field line configuration around a moon. The initial discovery of the Ganymede dipole in the magnetometer data was, however, complemented by detection of surface loss cones, consistent with dipole field geometry, in magnetic pitch angle distributions of energetic particles measured by the Energetic Particles Detector (EPD). It is of historic interest to note that Voyager 2 discoveries of the large tilts of planetary dipoles by magnetometer observations at Uranus and Neptune were also quickly confirmed by energetic particle measurements. This is because trapped energetic particles have predictable motions in smoothly varying magnetic fields, so precise predictions from magnetic field models can be made about positions of intensity and anisotropy variations due to moon interactions. In the Voyager data at Uranus and Neptune the moon sweeping signatures increased in depth at MeV energies for electrons and ions. Due to large gyroradii of high energy heavy ions, the Heavy Ion Counter (HIC) intensities of these iogenic ions at MeV/nucleon energies showed strongly anisotropic intensity variations, due to surface absorption, during many Galileo flybys of Io and Europa. Analysis of the HIC flyby data continues but lack of a permanent dipole at Io is consistent with the equatorial flyby observations. At Europa the HIC results to date indicate strong sensitivity to the induced dipole. Value of energetic ion anisotropy measurements for the moon magnetic environments could be enormously improved by increased energy, mass, and angular resolution at keV to MeV energies covered by EPD and at MeV/nucleon energies covered by HIC. These resolution increases, also allowing isotopic measurements of ions for composition objectives, could be enabled by substantially greater power, data rate, instrument mass, and near-moon observation times to be provided by the Jupiter Icy Moons Orbiter (JIMO) mission. Improved energy and directional resolution for energetic electrons above 10 keV to tens of MeV are also needed to model global distributions of incidence through magnetic environments onto the moon surfaces for computation of depth-dependent radiation dosages relevant to surface chemistry and for astrobiology applications. The latter include production rates to meter depths in the icy regoliths for oxidants and other chemical resources for life in the putative subsurface oceans, assuming efficient geologic transport downward through the overlying ice crust at least for Europa, and destruction rates to the same depths for biochemical signatures of life that may be found on the moon surfaces by remote and in-situ measurements. Our ability to resolve the potential oceanic abode of life within Europa, and to confirm the presence of oceans within Ganymede, Callisto, and perhaps (extended mission?) Io, should vastly improve from measurements provided by energetic particles as complementary to those from magnetic fields, orbital gravimetric analysis, laser/radar altimetry, and the newer techniques for planetary missions of active radio sounding for ionospheric imaging, local magnetic field line tracing via guided echoes, and determination of subsurface stratigraphy.

4. CONTRACT PUBLICATIONS AND PRESENTATIONS

A wide variety of materials have been published, presented, or are in preparation or review from various members of our research collaboration. The following lists are cumulative mostly from 2003 onward and will be updated for subsequent reports focusing on different specific areas. The asterisk symbol (*) marks those items added since the last report. Underlined names are for lead authors and co-authors who are members of our investigation team. Some earlier papers by team members (names also under-lined) are among those listed above in Section 6.

4.1 Journal and Book Articles

- Carlson, R. W., M. S. Anderson, R. E. Johnson, R. Mehlman, J. H. Shirley, and J. A. Mosher, Distribution of hydrated sulfuric acid on Europa, *Icarus*, in press, 2003.
- Cooper, J. F., R. E. Johnson, B. H. Mauk, H. B. Garrett, and N. Gehrels, Energetic Ion and Electron Irradiation of the Icy Galilean Satellites, *Icarus*, **149**, 133-159, 2001.
- Cooper, P. D., R. E. Johnson, and T. I. Quickenden, A review of possible optical absorption features of oxygen molecules in the icy surfaces of outer solar system bodies, *Plan. Sp. Sci.*, **51(3)**, 183-192, 2003a.
- *Cooper, P. D., R. E. Johnson, and T. I. Quickenden, Hydrogen peroxide dimers and the production of O₂ in icy satellite surfaces, *Icarus*, **166**, 444-446, 2003b.
- *Greeley, R., et al., including J. F. Cooper, Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO), draft, Dec. 2003.
- Johnson, R. E., R.W. Carlson, J. F. Cooper, C. Paranicas, M. H. Moore, and M. Wong, Radiation Effects on the Surfaces of the Galilean Satellites, in *Jupiter - The Planet, Satellites and Magnetosphere*, F. Bagenal, W. McKinnon, and T. Dowling (Eds.), Space Science Series, University of Arizona Press, Tucson, in press, 2003a.
- *Johnson, R. E., T. I. Quickenden, P. D. Cooper, A. J. McKinley, and C. G. Freeman, The production of oxidants in Europa's surface, *Astrobiology*, **3(4)**, 823-850, 2003b.
- Mauk, B. H., D. G. Mitchell, S. M. Krimigis, E. C. Roelof, and C. P. Paranicas, Energetic neutral atoms from a trans-Europa gas torus at Jupiter, *Nature*, **421**, 920-922, 2003a.
- Shematovich, V. I., and R. E. Johnson, Near-surface oxygen atmosphere at Europa, *Adv. Sp. Res.*, **27**, 1881-1888, 2001.
- *Shematovich, V. I., R. E. Johnson, J. F. Cooper, and M. C. Wong, Surface-bounded atmosphere of Europa, submitted to *Icarus*, 2004.

4.2 Conference Presentations

- Carlson, R. W., Depth profile of radiolytic fluence on Europa: Implications for remote sensing and in-situ analyses, American Astronomical Society, DPS meeting #35, #17.01, 2003.
- Cooper, J. F., The space physics of life, contributed poster, 2003 General Meeting of the NASA Astrobiology Institute, Arizona State University, Tempe, Arizona, Feb. 10-14, 2003a.
- Cooper, J. F., Radiolytic Coupling of the Jovian Magnetosphere to the Chemical Composition of Europa's Atmosphere, Surface, and Sub-Surface Ocean, contributed talk, Europa Focus Group Arctic Ice Field Conference, Barrow, Alaska, April 24 - 27, 2003b.

- Cooper, J. F., The Jupiter Icy Moons Orbiter Mission, oral presentation at Tuesday UVA / NRAO Astronomy (TUNA) Lunch Talks, University of Virginia, Charlottesville, VA, Oct. 7, 2003c.
- *Cooper, J. F., Europa's Oceanic, Surface, and Atmospheric Interactions with the Jovian Magnetosphere, Geophysical Institute Seminar, University of Alaska at Fairbanks, Nov. 14, 2003d.
- *Cooper, J. F., Energetic Particles as Probes of Magnetic Environments for Galilean Moons at Jupiter, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract SM22B-0249, 2003e.
- Green, J. L., B. W. Reinisch, P. Song, S. F. Fung, R. F. Benson, W. W. L. Taylor, J. F. Cooper, L. Garcia, and D. Gallagher, Remote radio sounding science for JIMO, Abstract 9013, Forum on Concepts and Approaches for Jupiter Icy Moons Orbiter, Lunar and Planetary Institute, Houston, June 12-14, 2003a.
- *Green, J. L., B. W. Reinisch, P. Song, S. F. Fung, R. F. Benson, W. W. Taylor, J. F. Cooper, L. Garcia, T. Markus, D. Gallagher, and P. Gogineni, Remote Radio Sounding Science For JIMO, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract SM12B-04, 2003b.
- Johnson, R. E., P. D. Cooper, and T. L. Quickenden, Radiolytic formation of oxidants at Europa, American Astronomical Society, DPS meeting #35, #17.04, 2003c.
- *Johnson, R. E., J. F. Cooper, V. I. Shematovich, R. W. Carlson, M. C. Wong, F. Leblanc, and J. H. Waite, Atmospheres Produced by Magnetospheric Irradiation of Jupiter's Icy Galilean Moons, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract SM12C-03 Invited, 2003d.
- *Khurana, K. K., W. S. Kurth, J. F. Cooper, J. H. Waite, J. E. Connerney, J. L. Green, F. Crary, W. R. Paterson, R. E. Johnson, C. Paranicas, and B. H. Mauk, Field and Plasma Science with the Jupiter Icy Moons Orbiter (JIMO), *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract P11C-07 Invited, 2003.
- *Markus, T., P. Gogineni, J. L. Green, B. W. Reinisch, P. Song, S. Fung, R. F. Benson, W. L. Taylor, J. F. Cooper, L. Garcia, and D. L. Gallagher, Surface Penetrating Radar Simulations for Jupiter's Icy Moons, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract P31B-1063, 2003.
- Mauk, B. H., C. P. Paranicas, and J. F. Cooper, Diagnosing interactions between jovian satellites and their energetic charged and neutral particle environments, Abstract 9089, Forum on Concepts and Approaches for Jupiter Icy Moons Orbiter, Lunar and Planetary Institute, Houston, June 12-14, 2003b.
- Moore, M. H., R. L. Hudson, and R. W. Carlson, Role of radiolysis in the formation and destruction of molecules on the Jovian icy moons, American Astronomical Society, DPS meeting #35, #05.03, 2003.
- Shematovich, V. I., R. E. Johnson, and J. F. Cooper, Gas-surface chemical exchange in the near-surface atmosphere of Europa, *Eos Trans. AGU*, 83-47, Fall Sci. Meet. Suppl., Abstract P61A-0342, 2002.
- Shematovich, V. I., R. E. Johnson, and J. F. Cooper, Surface-bounded oxygen atmosphere of Europa, contributed poster, *EGS - AGU - EUG Joint Assembly, Nice, France, April 6-11, 2003*, Abstract EAE03-A-13094, 2003a.
- *Shematovich, V., R. E. Johnson, J. F. Cooper, and M. C. Wong, Supply of trans-Europa Neutral Torus by the Surface-bounded Atmosphere of Europa, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract SM22B-0248, 2003b
- Wong, M., J. Berthelier, R. Carlson, J. Cooper, R. Johnson, S. Jurac, F. Leblanc, and V. Shematovich, Measurement of surface composition for the icy galilean moons via neutral and

ion mass spectrometry from orbit with JIMO, Abstract 9037, Forum on Concepts and Approaches for Jupiter Icy Moons Orbiter, Lunar and Planetary Institute, Houston, June 12-14, 2003.

4.3 Related Proposals

Collier et al. (2003). "Remote Sensing the Jovian Plasma Environment Using Low Energy (10 eV-4 keV) Neutral Atom Imaging", by J. F. Cooper, R. E. Johnson, and V. I. Shematovich as Co-Is for GSFC proposal of M. R. Collier, NASA Goddard Space Flight Center, submitted to NRA-03-OSS-01-HCIPE, High Capability Instruments for Planetary Exploration, for 2004-2007, Oct. 2003.

Reinisch et al. (2003). "Planetary Advanced Radio Sounder", by J. F. Cooper as Co-I for U. of Mass. Lowell proposal of B. W. Reinisch, University of Massachusetts at Lowell, submitted to NRA-03-OSS-01-HCIPE, High Capability Instruments for Planetary Exploration, for 2004-2007, Oct. 2003.