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Studies for the 3-Dimensional Structure, Composition, and Dynamics of Io's Atmosphere

ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.

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Report for the Period of
May 19, 2000 to May 18, 2001

I. Introduction

The overall objective of this project is to advance our understanding of the three-dimensional structure, composition, and dynamics of Io's atmosphere and its significant changes as Io moves in its orbit about Jupiter and undergoes complex, coupled interactions with the corotating plasma torus that shape its atmosphere, ionosphere, and loss of neutral and plasma species. The proposal provides a timely, unique, and very promising approach to this problem. It combines state-of-the-art hydrodynamic and kinetic theory atmospheric models with new ground-based, HST, and Galileo observations which, for the first time, provide us with spatially resolved images for the distribution of several atomic species (O, S, newly discovered H, and hopefully, Na) in Io's atmosphere and also with ten new ionospheric profiles. It is proposed to undertake in a systematic way the natural extension and refinement of an already established multi-species hydrodynamics model with photo- and gas-phase chemistry for Io's atmosphere (Wong and Johnson 1996) and a hybrid fluid/kinetic model (Marconi, Dagum and Smyth 1996) to establish a fundamental base upon which to study Io's atmosphere more fully and the effects of the magnetosphere on the atmosphere because of plasma chemistry, ion-driven gas escape, and electromagnetic heating processes near the satellite. The three-year research plan is summarized in Table 1.

Table 1. Three Year Research Plan

Model	Year 1	Year 2	Year 3
2-D Hydrodynamic	Add H chemistry, ion & electron processes, and evaluate their effects.	Perform support model calculations for the 3-D fluid and the 2-D hybrid models; add ionospheric chemistry.	
2-D Hybrid	Implement simple chemistry in the model.	Add streamlines; undertake calculations to study the non-equilibrium departures of the hydrodynamic model and the escape of gases from the atmosphere.	
3-D Hydrodynamic	Incorporate heating, chemistry, electron & ion processes evaluated above in the 2-D model.	Test model; undertake modeling studies for O, S, H, Na observations and also for different locations of Io about Jupiter; begin integration of streamlines from E & M solution; add ionospheric chemistry.	
Electromagnetic Interaction	--------	Develop code to solve for the electric and magnetic fields and the streamlines.	Complete development; undertake coupling of the interaction model & the atmospheric model.

II. Summary of Work Performed in the Second Year

In the second project year, research efforts have focused on (1) evaluating the effects of hydrogen and chlorine chemistry in the two-dimensional hydrodynamic model for Io's atmosphere, and (2) developing a three-dimensional hydrodynamic model for Io's atmosphere.

Progress has been much slower than expected because of an extended illness of the Principal Investigator that impacted most of the project year and because of staffing changes. Much of the research work was therefore postponed to the third project year.

2.1 Hydrogen and Chlorine Chemistry for Io's Atmosphere

Exploring the impact of new chemistry for H and Cl in Io's atmosphere was initiated this year. The presence of atomic hydrogen in Io's atmosphere was recently identified spectroscopically by Trafton (2000) in Lyman-α (1216 Å) emission corresponding to several hundred Rayleighs from measurements acquired with the Goddard High Resolution Spectrograph (GHRS) of the Hubble Space Telescope (HST). The likely presence of atomic hydrogen in Io's atmosphere was suggested earlier by Frank and Paterson (1999) from the detection in Galileo spacecraft PLS data of H^+ pickup ions near Io and by the analysis of Galileo spacecraft plasma wave (PWS) data near Io by Chust et al. (1999). The detection in Io's atmosphere of atomic chlorine in the emission lines at 1379.5 Å and 1347.2 Å and of atomic hydrogen in Lyman-α emission was also more recently reported by Retherford et al. (2000) from observations acquired with the Space Imaging Spectrograph (STIS) of HST. The likely presence of atomic chlorine in Io's atmosphere was expected from detections in the plasma torus of Cl^+ emission at 8579 Å from groundbased observations by Kuppers and Schneider (2000) and of Cl^+ emission at 1071 Å and Cl^{++} emission at 1011 Å from Far Ultraviolet Spectroscopic Explorer (FUSE) measurements by Feldman et al. (2000).

If volcanoes are the primary source of chlorine species in the atmospheric, the most likely existing parent gas molecules have been studied by Fegley and Zolotov (2000) using thermochemical equilibrium calculations for an O-S-Na-K-H system. If the abundance of (Na + K)/Cl >1, the major Cl gases are chlorides of Na and K, the major Na gases are NaCl, Na, and $(NaCl)_2$ and the major K gases are KCl, Na, and $(KCl)_2$. If the abundance of (Na + K)/Cl <1, the major Cl gases change to Cl_2, Cl, S_2Cl, and SCl_2. Fegley and Zolotov suggest that the abundance of H-bearing gases are likely insignificant for plausible hydrogen abundances in Io's atmosphere.

An initial search for known reactions involving the major species in Io's atmosphere (SO_2, SO, O, S, O_2) and the minor species H and Cl (and likely parent molecules and chemical products) has produced the list in Table 2. The list of reactions does not contain many major-minor species reactions. In addition, some of the species abundances or their reaction rates are small so that certain reactions can be ignored in developing a closed chemical system. More work is, however, needed to identify additional important reactions and to determine the relevant rates of all reactions so as to develop an appropriately closed system for the H and Cl chemistry in Io's atmosphere.

Table 2. Chemical Reactions for H and Cl Species

Reactions				Rate
Cl_2	$+ h\nu$	$\rightarrow$ Cl	+ Cl	J1
H_2	$+ h\nu$	$\rightarrow$ H	+ H	J2
ClO	$+ h\nu$	$\rightarrow$ O	+ Cl	J3
NaCl	$+ h\nu$	$\rightarrow$ Na	+ Cl	J4
HCl	$+ h\nu$	$\rightarrow$ H	+ Cl	J5
Cl_2	+ O	$\rightarrow$ Cl	+ ClO	k1
Cl_2	+ Na	$\rightarrow$ Cl	+ NaCl	k2
ClO	+ SO_2	$\rightarrow$ Cl	+ SO_3	k3
ClO	+ SO	$\rightarrow$ Cl	+ SO_2	k4
ClO	+ O	$\rightarrow$ Cl	+ O_2	k5
ClO	+ OH	$\rightarrow$ Cl	+ HO_2	k6
Cl	+ OH	$\rightarrow$ HCl	+ O	k7
Cl	+ H_2	$\rightarrow$ HCl	+ H	k8
H	+ Cl	$\rightarrow$ HCl	+ Cl	k9
HCl	+ O	$\rightarrow$ Cl	+ OH	k10
HCl	+ OH	$\rightarrow$ Cl	+ H_2O	k11
H_2	+ O	$\rightarrow$ H	+ OH	k12
H_2	+ OH	$\rightarrow$ H	+ H_2O	k13

If, for example, either Cl_2 or NaCl were the parent molecule for chlorine and if the hydrogen species were not included, a particular simple closed system for chlorine chemistry is obtained by including only the reactions labeled by the rates J1, J3, J4, k1, k2, k4, and k5, since the reaction rate k3 is many orders of magnitude smaller than k4 and the abundance of SO_2 is no more than about an order of magnitude larger than SO. As a first step in assessing the impact of chlorine chemistry, this simple closed system has been added to the SO_2 and Na chemistry already included in the two-dimensional multi-species hydrodynamic model for Io's atmosphere of Wong and Smyth (2000). The complete set of reactions for this chemistry is summarized in Table 3. At the end of the second project year, two-dimensional hydrodynamic model calculations are in progress to determine the two-dimensional [altitude and solar zenith angle (noon-to midnight)] structure of the chlorine species and their impact on the sodium species, which are coupled because of reactions J10 and k11 in Table 3. In the calculation, Cl_2 is assumed to be the parent molecule for chlorine. The surface source strength of Cl_2 will be varied relative to the surface source strength of the sodium bearing species to explore the relative compositional behaviors of these two chemical families in the atmosphere. These calculations will be presented (Smyth et al. 2001) at the meeting "Jupiter: The Planet, Satellites and Magnetosphere" scheduled for June 24-30, 2001 in Boulder, Colorado.

(CFDLIB). CFDLIB is a computer code developed at Los Alamos National Laboratory. It is a collection of hydrocodes using a common data structure and a common numerical method, for problems ranging from single-field, incompressible flow, to multi-species, multi-field, compressible flow. The computer code solves numerically the equations of transient, multi-material, compressible fluid mechanics. This code has been installed on an in-house SGI Power Challenge L computer with 10 R-10000 processors. A test case run of has been successfully executed.

In order to apply the code to the Io's atmosphere, a 3-D spherical coordinate mesh has been created using two blocks, which connect to each other. One block forms the east hemisphere and one the west hemisphere. The other two ends of the blocks are shrunken to form the poles. A simple version employed in initial testing of the model had 9 boxes in the latitude direction, 20 boxes in the longitude direction and 30 layers from the Io's surfaces to 500 km, evenly divided. The number of boxes is to be increased after the testing phase is completed. Io's gravity, which varies with altitude, has been added. The code was tested for hydrostatic and simple dynamic states of Io's atmosphere. For the hydrostatic state, an instability developed that prevented the code from running to completion. We are investigating the source of the instability. With the loss of the staff scientist early in the fourth quarter of this second project year who was developing this code, this investigation will be postponed until the third project year.

The gas species SO_2, SO, S, O, O_2, Na, NaS, and NaO have been included in the three-dimensional model. These species are the same as those adopted in the two-dimensional model calculations for Io's atmosphere published by Wong and Smyth (2000). Subroutines have been included in the three-dimensional code for adding energy sources, and the code is now ready for adding plasma heating, Joule heating, solar heating, and non-LTE cooling in the atmosphere. In addition, subroutines for the sources and losses of chemical species have been included in the code. A utility based upon IDL to display graphically the three-dimensional model output has also been developed to facilitate visualization of current diagnosis and future model results. Once the three-dimensional code for Io's atmosphere is operative, it will be verified by comparing two-dimensional calculations with the published two-dimensional model calculations of Wong and Smyth (2000).

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Research work is discussed (1) for the exploration of new H and Cl chemistry in Io's atmosphere using the already developed two-dimensional multi-species hydrodynamic model of Wong and Smyth (2000), and (2) for the development of a new three-dimensional multi-species hydrodynamic model for Io's atmosphere.

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