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NASA Solar System Exploration Division
Planetary Atmospheres Program

STUDIES FOR THE LOSS OF ATOMIC AND MOLECULAR SPECIES FROM IO

Ongoing Research: Composition/Structure/Dynamics of Planetary Satellite Atmospheres

Final Report for the period: 5/1/93 - 6/30/97

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I. INTRODUCTION

The general objective of this project has been to advance our theoretical understanding of Io's atmosphere and how various atomic and molecular species are lost from this atmosphere and are distributed in the circumplanetary environment of Jupiter. This grant has provided support for the activities of Michael Combi at the University of Michigan in collaboration with a larger project awarded to Atmospheric & Environmental Research, Inc., with primary principal investigator William H. Smyth. Michael Combi is the Principal Investigator and Project Manager for the Michigan grant NAGW-3585. This Michigan grant has provided for a continuation of a collaboration in related efforts beginning in 1981, and with the object to develop and apply sophisticated theoretical models to interpret and to relate a number of new and exciting observations for the atmospheric gases of the satellite. The ability to interpret and then to relate through the theoretical fabric a number of these otherwise independent observations are a central strength of this program. This comprehensive approach provides a collective power, extracting more from the sum of the parts and seeing beyond various limitations that are inherent in any one observation. Although the approach is designed to unify, the program is divided into well-defined studies for the likely dominant atmospheric gases involving species of the SO_2 family (O, S, SO, O_2, SO_2) and for the trace atmospheric gas atomic sodium and a likely escaping molecular ion NaX^+ (where NaX is the atmospheric molecule and X represents one or more atoms).

The relative abundance of the members of the SO_2 family and Na at the satellite exobase and their spatial distributions beyond in the extended corona of Io are not well known but will depend upon a number of factors including the upward transport rate of gases from below, the velocity distribution and corresponding escape rates of gases at the exobase, and the operative magnetospheric/solar-photon driven chemistry for the different gases. To date in the corona and near extended neutral clouds of Io, O and S have been observed in their UV emission lines over a number of years by IUE (Ballester et al. 1987; Ballester 1989; McGrath 1991), O has been detected in the optical (6300 Å) emission by ground-based observers (Schneider et al. 1989; Scherb and Roesler 1990; Brown 1991; Scherb 1991, 1992; Scherb and Smyth 1993). Na has been observed in the optical (5890 Å, 5896 Å) extensively for 20 years and most recently by Schneider et al. (1987), Schneider (1988 and 1991a). Although SO_2 has been observed in the local atmosphere of Io (Pearl et al. 1979; Lellouch et al. 1990, 1992; Lellouch 1996; Ballester et al. 1994), the angular extent of Io's surface covered by this gas and its vertical structure are still uncertain. Current wisdom indicates that there is at least a thin global atmosphere, with surface densities of at least a few x 10^{11} cm^{-3} in equilibrium with surface (SO_2) frost, as well as locally thick pockets produced by volcanic plumes. Observations of SO_2^+ at ~5.3 Jupiter radii from the planet, and (most importantly) well inside Io's orbit (~5.9 R_J) by the Voyager 1 PLS instrument (Bagenal 1985) suggests that SO_2 is present at the exobase of Io with the atomic species O, S and Na, and possibly other polyatomic species (NaX^+?), and may escape in large quantities despite its short 40-hour photodissociation lifetime and very short ~1-hour electron impact dissociation lifetime in the plasma torus. The likely presence of molecules, or at least molecular ions, has further been suggested as a plausible mechanism to explain an unusually shaped fast sodium jet whose source is tied to the ion precursor species that is apparently locked into magnetic flux tubes in the corotating plasma torus (Schneider et al. 1991)

The scientific objectives of the larger collaborative program between AER, Inc., and the University of Michigan have been to undertake theoretical modeling studies to simulate the distributions of the exospheric gases in Io's corona and extended clouds, to investigate the importance of the various physical processes that shape their relative abundances, and with these tools to analyze observations of O, S and Na obtained by four observers: M.A. McGrath of the Space Telescope Science Institute and G.E. Ballester of the University of Michigan who each have obtained Hubble Space Telescope observations of O and S near Io, F. Scherb who continues an effort to obtain 6300 Å OI observations as part of the University of Wisconsin Fabry-Perot program, and N.M. Schneider of the University of Colorado who obtained an extensive set of spectral and spatial observations of the Na emission near Io in the D-lines.

The last year of the project actually represents the first year of a three-year effort to study observations of local and near-extended atmosphere of Jupiter's natural satellite Io. Because of the transfer of grant administration from NASA Headquarters to NASA Goddard Space Flight Center, the project was artificially cut-off at the end of the first year and a new 2-year grant has just been started and funded out of NASA/Goddard. Therefore, the work is still ongoing.

Progress of Work

One important task performed at Michigan has been to support AER in the general area of modeling the Na and SO_2-family clouds. Another major task has been the generalization of the extended Io sodium cloud model to simulate the ion-precursor of sodium that is the apparent source of the fast sodium jet observed by Schneider et al. (1991). The ultimate goal is a quantitative test of the molecular ion hypothesis with a model that is comparable to the general sodium cloud model published by us previously (Smyth and Combi 1988 a&b). A detailed comparison of observations with such a model will help to probe the feasibility of such a source and to examine the rates and scale lengths associated with the decay of the ion precursor.

The first task comprised a comprehensive modeling study which coordinated and analyzed a broad range of Na D-line emission profiles with the mutual eclipse absorption profiles of the inner corona by Schneider et al. (1991) using models developed over many years (Smyth and Combi 1988a &b) to provide a consistent flux-speed distribution for escape of sodium by Io which appears to be produced by incomplete cascade sputtering of the atmosphere. Neither a thermal source nor a direct atmospheric sputtering source can simultaneously explain the inner corona probed by the eclipse data as well as the outer corona and B-cloud probed by the emission data. The incomplete cascade sputtering process nicely explains the entire observed Na distribution. A preliminary version of the results was presented by Smyth and Combi (1995). The paper (Smyth and Combi 1997) which resulted has appeared this year in *Icarus*. A copy of it is attached to this report. During this last year of the project, some final revised calculations had to be made to complete the work.

The second major part of the work performed under this grant was the construction of a computer model to simulate the Na molecular-ion jet source. It is a substantial modification of our former (Smyth and Combi 1991) zenocorona (or magneto-nebula) extended Na model which was developed also at the University of Michigan. The new zenocorona model is functionally equivalent to that used by Wilson and Schneider (1994) in the analysis of their images of fast sodium near Io. Figure 1 shows the model results for fast sodium corresponding to image 90s2339 of Wilson and Schneider (1994) with Io at an orbital phase of 209^{o} and at a system III longitude of 297^{o}. The picture reproduces the observed sodium image very well. The model uses the same solution for the two-body orbit problem as discussed by Combi and Smyth (1988a) in the context of their comet model. The previous zenocorona model (Smyth and Combi 1991) integrated particle orbits using a fourth order Runge Kutta routine. The old procedure was needed for computing Jupiter-centered orbits and accounting for radiation pressure. However, except for very large distances from Jupiter, the radiation pressure acceleration is of minor importance for fast-moving Na atoms. In the new scheme the end point of each particle trajectory can be calculated from standard orbit extrapolations, and explicitly accounts for Jupiter gravity. This version of the model can be applied to much slower-speed sodium. In this model simulations with contributions from millions of particles can be run on desktop workstations in just a few minutes, greatly increasing the particle statistics, and thereby reducing model uncertainty (noise). The model in Figure 1 contains contribution from 2 million simulation particles. The model accounts for the emission of precursor molecular ions from Io, which bounce along the magnetic-field flux tubes as described in the paper by Cummings et al. (1980). Sodium atoms are emitted with a given decay lifetime from the molecular ion source. The model will be used during the continuation grant, once an improved Galileo-epoch version of the plasma torus description is made available by our AER collaborators.

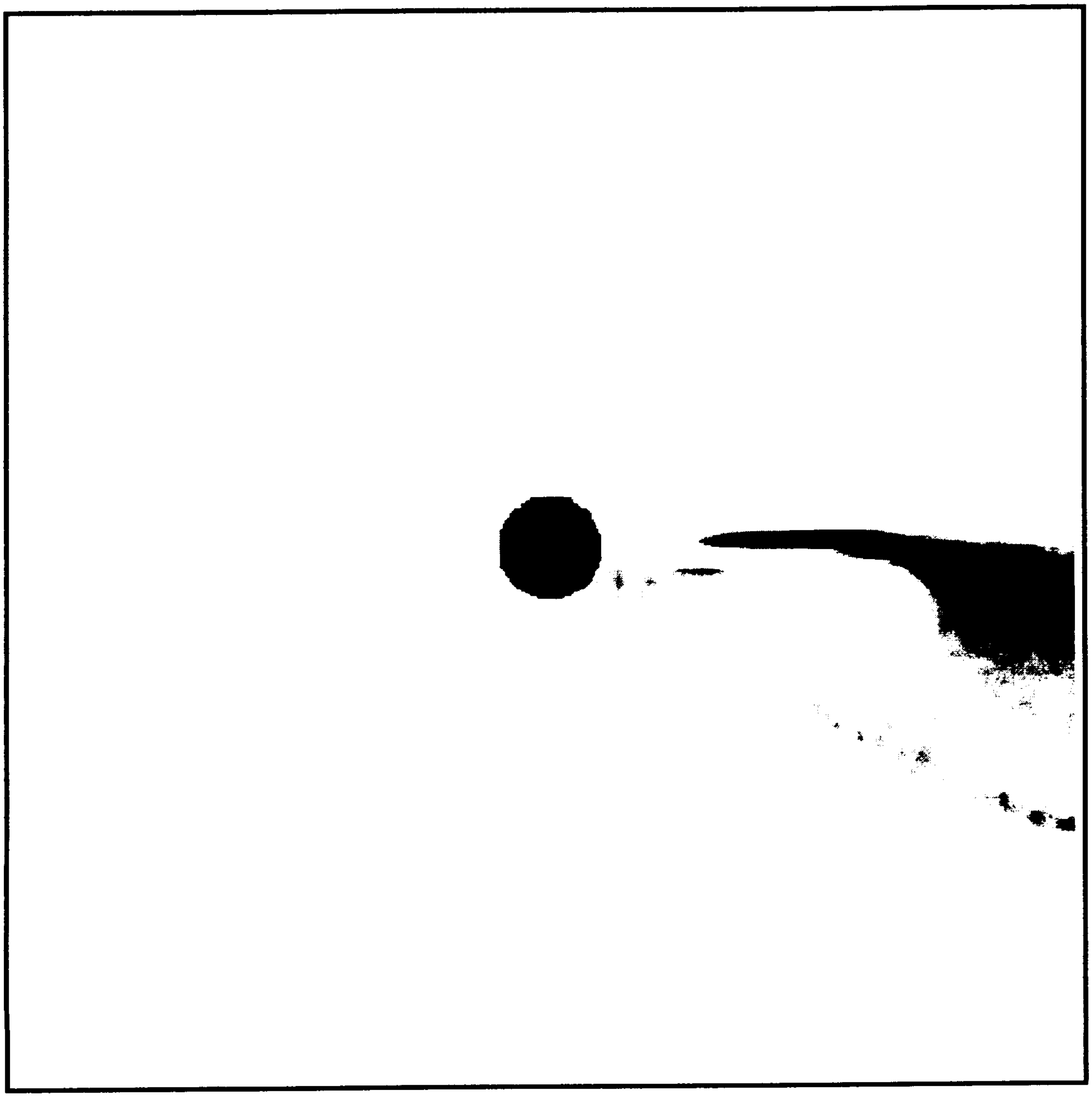

Figure 1. Model for a Fast Molecular-Ion Source for the Peculiar Sodium Features near Io. Shown is a gray-shade plot of sodium D2 emission produced by sodium emitted from a decaying molecular ion source. The source deposits molecular ions on a flux tube in the plasma torus at Io, which then continue to undergo normal bounce motions about the centrifugal equator as the torus corotates. These ions then decay by dissociative recombination, forming the fast sodium atoms which are observed. The black circle represents Jupiter. For the model Io is to the right of Jupiter and the source of the jet. See text for further details.

Program for the Continuation of Work under the New Two-Year Grant

Work will continue for the remaining two years on the planned topics. Observations of neutral sulfur and oxygen near Io, taken by the Hubble Space Telescope (HST) and ground-based telescope observations of neutral sodium in the near and near-extended atmosphere taken by Dr. N. Schneider, University of Colorado, and Dr. L. Trafton, University of Texas will be analyzed. Dr. Combi is a Co-Investigator on the HST observing team headed by Dr. G. Ballester, also of the University of Michigan, and will provide an interface between the observing team and the acquisition and analysis of the data for this proposal, in addition to collaborating with the analysis. Model analysis of the sodium observations from N. Schneider taken in 1987 and the new added analysis of a larger set of data from L. Trafton taken starting in 1986 and continuing to the present will be performed. The most interesting data are 1987 observations from L. Trafton taken on the same days as some taken by N. Schneider, but where the former observed the spatial distribution of the near extended sodium in the north-south direction where the latter observed east-west. The object of these model analyses is to study the angular part of the source distribution, the source strength, the general Io/Jupiter-magnetosphere interaction, and the variations of all three with time, system-III longitude, and Io's orbital phase.

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