AER

(NASA-CR-168725) Io: ESCAPE AND IONIZATION OF ATMOSPHERIC GASES Interim Report, 15 Apr. - 15 Oct. 1981 (Atmospheric and Environmental Research) 25 p HC A02/MF A01 CSCL 03B G3/91

N82-22125

Unclas 15208

ATMOSPHERIC & ENVIRONMENTAL RESEARCH, INC.
Cambridge, Massachusetts

IO: ESCAPE AND IONIZATION

OF ATMOSPHERIC GASES

William H. Smyth

Atmospheric and Environmental Research, Inc.
840 Memorial Drive
Cambridge, Massachusetts 02139

October 15, 1981
Interim Report for Period
April 15, 1981 - October 15, 1981

Prepared for
NASA Headquarters

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. One	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Io: Escape and Ionization of Atmospheric Gases		5. Report Date October 1981
		6. Performing Organization Code
7. Author(s) William H. Smyth		8. Performing Organization Report No.
9. Performing Organization Name and Address Atmospheric and Environmental Research, Inc. 840 Memorial Drive Cambridge, Massachusetts 02139		10. Work Unit No.
		11. Contract or Grant No. NASW-3503
		13. Type of Report and Period Covered Interim Report April 15 - October 15 1981
12. Sponsoring Agency Name and Address NASA Headquarters Headquarters Contract Division Washington, DC 20546		14. Sponsoring Agency Code HWC-2
15. Supplementary Notes		

16. Abstract

Models for the Io oxygen clouds have been improved to calculate the two-dimensional sky-plane intensity of the 1304 Å emission and the 380 Å emission of atomic oxygen, in addition to the 6300 Å emission intensity. These three wavelength emissions are those for which observational measurements have been performed by ground-based, rocket, Earth-orbiting satellite and Voyager spacecraft instruments. Comparison of model results and observations suggests that an oxygen flux from Io of about 3×10^9 atoms $cm^{-2} sec^{-1}$ (i.e., an overall source rate of 1.2×10^{27} atoms sec^{-1}) is required for agreement. Future refinements in the model could increase the overall source rate by a factor of two. Model results for the satellite-ion source, created by magnetospheric ionization of the oxygen cloud, may provide an explanation for the newly discovered Io-correlated energy source of the plasma torus (Sandel, 1981). Quantitative analysis of the Io sodium cloud has focused upon the initial tasks of acquiring and preliminary evaluation of new sodium cloud and Io plasma torus data.

17. Key Words (Selected by Author(s)) satellite atmospheres planetary magnetospheres		18. Distribution Statement	
19. Security Classif. (of this report) unclassified	20. Security Classif. (of this page) unclassified	21. No. of Pages 24	22. Price*

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

I. SUMMARY OF RESEARCH PROGRESS FIRST AND SECOND QUARTER

First Year Strategy

Due to reduced budgetary support available during the first year, the strategy adopted for our data analysis program during the first year was modified to focus more effort upon the exploratory modeling of the Io atomic oxygen cloud and less effort upon the data analysis of the Io sodium cloud. The analysis of the Io sodium cloud has thus been restricted to acquiring and preliminary evaluation of Io sodium cloud and Io plasma torus data. This strategy will allow the necessary groundwork to be prepared so that the more time consuming and quantitative sodium data analysis, some of which was originally scheduled for the first year, may be initiated no later than the beginning of the second year. This strategy will also allow important model results for the Io atomic oxygen cloud, of immediate interest to a number of other magnetospheric investigators, to be obtained more rapidly.

Progress in Modeling the Io Oxygen Cloud

Model Improvements

Significant progress has already been made in the first year in exploratory modeling of the Io atomic oxygen cloud. The oxygen cloud model has been improved so that it is now capable of calculating not only the two-dimensional sky-plane intensity of the 6300 Å emission of atomic oxygen (illustrated by earlier model results in Figure 1), but also the 1304 Å emission and the 880 Å emission of atomic oxygen. These three wavelength emissions are those for which observational measurements have been performed by ground-based, rocket, Earth-orbiting satellite and Voyager spacecraft instruments as summarized in Table 1.

Improvements in the cloud model have also been made in the two-dimensional data for the Io plasma torus electrons. These data are used to determine the lifetime of oxygen atoms in the Jovian environment as well as the volume exciation rates for the three emission lines of atomic oxygen resulting from electron impact. The two-dimensional ionization lifetime for oxygen, produced by the Io plasma torus electrons and corresponding to the results of Figure 1, is shown in Figure 2. This lifetime is radially highly-asymmetric about the orbital position of Io (5.9 R_J) such that the portion of the atomic oxygen cloud that forms inside the satellite orbital radius is significantly more dense and extended than the portion of the cloud outside of the orbit, as illustrated in Figure 3. The instantaneous oxygen-ion creation rate produced from this ionization of the cloud atoms by the Io plasma torus is shown in Figure 4 and is (as expected) somewhat complementary to the spatial distribution of the neutral gas cloud in Figure 3.

Model Results for the Neutral Oxygen Cloud

The flux of oxygen atoms from Io can be determined by comparison of model results for the 6300 Å emission intensity with the ground-based observation of Brown (1981). In our most recent calculations, Brown's measured value of 8 ± 4 Rayleighs corresponds to an oxygen flux of about $(3 \pm 1.5) \times 10^9$ atoms cm^{-2} sec^{-1} from Io's surface or an overall source rate of $(1.2 \pm 0.6) \times 10^{27}$ atoms sec^{-1}. This is 30% of the value assumed for the oxygen flux in the model results of Figure 1. This value for the overall source rate is only a preliminary estimate which will be refined upward in future calculations by incorporation of the four model improvements summarized in Table 2.

Specification of the oxygen atoms flux from the 6300 Å intensity data automatically determines the intensity of the 1304 Å emission and the 880 Å emission in the model calculation. In our most recent model calculations, the intensity of the 1304 Å emission is comparable to the 6300 Å emission intensity, while the intensity of the 880 emission is about five times smaller. These model results for the UV emissions are a little below the observational upper limits imposed by measurements summarized in Table 1 when the different slit sizes of the measuring aperatures on the sky plane are properly taken into account. More sensitive rocket and IUE satellite measurements or a longer analysis-sampling-time of select Voyager UVS data might therefore be able to provide a positive detection of one or both of these UV emssion lines. This has been brought to the attention of the UV investigators.

Model Results for the Satellite Ion Source

Specification of the overall source rate of oxygen atoms emitted by Io from the analysis of the observed 6300 Å intensity data also establishes the overall O^+ ion-creation rate of the neutral cloud. The neutral cloud may not, however, be the only source of O^+ ions for the Io plasma torus since direct escape of oxygen ions from the satellite or production of O^+ ions from dissociation of the oxygen bearing molecules or ions located in the large Jovian environment might also occur. It would appear at present from discussion to be presented below, that the O^+ ion source from the neutral cloud is very significant if not, in fact, the dominant contributor to the satellite-ion source. Understanding of this satellite-ion source is very important since the fundamental conclusions that have emerged from recent observational and theoretical studies of Jupiter's magnetosphere are (1) that Io is the primary source of the Jovian magnetospheric plasma, and (2) that this plasma source is the key element that differentiates the character of the magnetosphere of Jupiter from that of the magnetospheres of the Earth and Saturn.

Model calculations of the spatial distribution of the satellite ion creation rate, as illustrated in Figure 3, are useful in supporting many related studies of Jupiter's magnetosphere. Five such studies are summarized in Table 3 for which some cooperative effort with each investigator has been established. Discussion here will be limited to the first of these subjects for which some interesting results have already been obtained.

The discovery of an Io-correlated energy source for the Io plasma torus was recently announced by Sandel (1981). His analysis of the Voyager UVS observations showed that the plasma downstream from Io is brighter in SIII 685 Å emission because of an elevated electron temperature. The mechanism that raised the electron temperature was estimated to operate within about 45° of the position of Io in its orbit and represented a time average power input of about 4×10^{11} watts or about 20% of the power radiated in the UV by the torus. This time average power input may well be associated with the spatial pattern of the instantaneous ion creation rate shown in Figure 3 if there exists an energy transfer mechanism that would rapidly thermalize the newly-created corotational ions and heat the plasma electrons in about one hour or less. A plausible candidate for this rapid energy transfer mechanism is the plasma wave-induced energy transfer process presently under evaluation by Smith et al. (1981). This transfer mechanism is based upon the pickup ion signature in the ion velocity distribution which drives a Post-Rosenbluth instability.

Using the overall oxygen ion creation rate of 1.2×10^{27} ions sec^{-1} obtained from our model results and assuming that an equal number of sulfur ions would also be produced near Io (similar to the results of Figure 3), a hot electron source located just ahead of Io's orbital position with an energy input of about 1.6×10^{11} watts or about 8% of the total energy radiated in the UV torus would be produced if a rapid energy transfer mechanism were operative. If the additional ionizations of the neutral oxygen and sulfur clouds produced by magnetospheric plasma charge exchange processes such as

$$
\begin{aligned}
O^+ + O &\rightarrow O + O^+ \\
S^{++} + O &\rightarrow S^+ + O^+ \\
O^+ + S &\rightarrow O + S^+ \\
S^+ + S &\rightarrow S + S^+ \\
S^{++} + S &\rightarrow S^+ + S^+
\end{aligned}
$$

were also included in the model, the overall oxygen supply rate and the overall ion creation rate are expected to be approximately doubled. In this case the model estimated value for the Io correlated energy source would then be about 3.2×10^{11} watts or about 16% of the total energy radiated in the UV plasma torus, which is in good agreement with the 20% value reported by Sandel (1981). The remaining 80% of the input energy to the plasma torus has been associated by Schemansky and Sandel (1981a,b) with an electron-electron heating mechanism in the magnetosphere that is stationary in local time on the dusk side of Jupiter.

Progress in the Analysis of the Io Sodium Cloud Data

The quantitative analysis of the Io sodium cloud data has been divided into five stages of activities which are summarized in Table 4. For model inversion of a given measurement, the sodium cloud model will be used to calculate a set of appropriate basis functions, which together with the measurement data, will then be the input for a constrained least square optimization problem. Best determined values of the physical model parameters will result from the data inversion method. The complete inversion scheme is diagrammed in Figure 5.

Efforts during the first year have been purposefully maintained at a low level because of budgetary reductions and have been restricted to the first stage of activity listed in Table 4, that of acquiring and preliminary evaluation of new sodium cloud and Io plasma torus data. New line profile data for the sodium cloud have, for example, been recently obtained from Trafton (1981). Additional line profile data are being sought from Trauger (1981a) and spatial intensity data have been requested from Mekler (1981). Improvements in the accuracy of plasma properties in the Io plasma torus are actively being sought from Bridge, Belcher, and Sullivan (1981) and from Pilcher and Morgan (1981).

II. PROGRAM FOR THE NEXT TWO QUARTERS

The two primary goals of the program are (1) to characterize the satellite emission conditions of sodium, oxygen and possibly sulfur operative at Io, and (2) to help characterize the satellite-ion source and the magnetic diffusion of ions in the near Io environment. To achieve these two objectives, two different approaches, initiated during the first two quarters will continue to be followed: (1) identification of the satellite emission characteristics for sodium atoms from the substantial neutral cloud data base obtained by Earth-telescope observations, and (2) exploratory modeling of the recently discovered Io oxygen cloud and of a possibly existing Io sulfur cloud.

Sodium Data Analysis

This first approach is very quantitative in nature. It involves acquiring a significant amount of sodium data and Io plasma torus data, much of which is summarized in Table 5, and using these data together with model calculations to extract physical information about the flux and velocity dispersion of sodium atoms emitted by the satellite. The data analysis scheme to be used in extracting this physical information is diagrammed in Figure 5. The actual data inversion is accomplished by applying either a non-linear method of Nelder and Mead (1965) or a constrained (or non-negative) least square optimization method formulated by Lawson and

Hanson (1974) utilizing Kuhn-Tucker conditions. The overall analysis is divided into five stages summarized in Table 4. The first stage will be completed in the next two quarters.

Oxygen and Sulfur Analysis

The second approach is more exploratory in nature. It seeks to provide model calculations for the Io atomic oxygen cloud and its associated satellite-ion source for comparison with the rather recently acquired Earth-based, rocket, Earth-orbiting satellite and Voyager spacecraft data. Similar exploratory model calculations for the neutral gas clouds of sulfur are also under consideration. Results obtained during the first two quarters of analysis of the Io oxygen cloud data have been most encouraging as discussed earlier. Four model improvements for the Io oxygen model that are currently under development are summarized in Table 2. In the next two quarters, emphasis will be focused upon implementing the first and third improvements of Table 2. The second improvement will require more time due to the complexity of the task. The fourth, and to some extent the third, improvements are dependent upon additional progress being made in the analysis of the Jovian plasma data obtained by the Voyager spacecrafts and in the more recent and very improved plasma torus observations obtained from ground-based telescopes (Pilcher et al., 1981; Morgan, 1981; Trauger, 1981b).

Observational data for the Io atomic oxygen cloud, summarized in Table 1, are expected to be significantly improved in the next year and will, together with model improvements, allow significantly better determinations of the emission characteristic of oxygen atoms from Io. Parallel improvements in model predictions of the ion-creation rate will automatically follow and will provide fresh input for the magnetospheric analysis summarized in Table 3. Modeling efforts in the next two quarters will continue to evaluate the impact of these newly acquired observational data.

Table 1

Observational Data for the Io Atomic Oxygen Cloud

Type of Observation	Investigator	Emission Wavelength (Å)	Brightness (Rayleighs)
1. Ground Based	R.A. Brown	6300	8 ± 4
2. Rocket Flight	H.W. Moos	1304	?
3. IUE Satellite	H.W. Moos	1304	<6
4. Voyager UVS	D.E. Shemansky	1304 880	<25 <10

Table 2

Model Improvements for the Io Oxygen Cloud Model

1. Consideration of the effects of the velocity dispersion of the oxygen atoms emitted by Io, instead of assuming a mean emission speed

2. Introduction in the model of the oscillating motion of the Io plasma torus about the satellite plane, which is presently omitted

3. Inclusion of change exchange lifetime processes in the model for the oxygen cloud atoms, which are presently omitted

4. Improvement in the accuracy of values for the electron and ion number densities and their temperatures in the Io plasma torus

Table 3

Impact of Newly Created Ions: Magnetospheric Analysis

Subject	Investigator
1. Io-Correlated UV Energy Source	B. R. Sandel
2. Plasma Instability Energy Transfer Mechanism	R. A. Smith
3. Pick-up-Ion Field-Aligned Currents	W. H. Ip
4. Radial Diffusion of Plasma	G. L. Siscoe
5. Charge Exchange Processes in the Plasma Torus	D. F. Strobel

Table 4

Five Stages of the Quantitative Analysis of the Io Sodium Cloud Data

(1) acquiring and quality evaluation of the different Voyager and Earth-based data sets,

(2) performing suitable calculations using our highly developed numerical models to generate the appropriate (physical model parameter dependent) basis functions for analysis of selected observations,

(3) applying a simplex technique for non-linear optimization or a least squares technique with constraint optimization to each selected observation and its set of model basis functions for inversion and extraction of physical information,

(4) evaluating the compatibility of physical model parameters deduced from analysis of different observations, and

(5) performing consistent and simultaneous analysis of complementary data sets.

TABLE 5

Io Sodium Cloud and Plasma Torus Data

I. **Voyager Data**

Type	Description	Data Source
Plasma Data	energy and density information of Jupiter's magnetospheric ions and electrons in and beyond the Io plasma torus	H. S. Bridge (MIT)
UVS Data	upper limits measurements for ultraviolet emission from neutral clouds of Io and measured emission of oxygen and sulfur ions in the hot torus	D. E. Shemansky (SSI)

II. **Earth-Based Data**

Type	Description	Data Source
Plasma Data	energy and density information of Jupiter's magnetospheric ions and electrons in the cooler inner plasma torus	Published (Brown, 1976, 1978)
	same	C. B. Pilcher (Univ. of Hawaii; private communication)
Spatial Sodium Data	one-dimensional spatial intensity profiles measured through an observing slit	Y. Mekler (Univ. Ramat Aviv, Israel; private communication)
	same	R. A. Brown (LPL; private communication)
	average spatial intensity measured through an observing slit	Published (Bergstralh et al., 1975, 1977)
	average spatial intensity measurements north and south of Io observed through a slit	Published (Trafton and Macy, 1975; Trafton, 1977)
	average spatial intensity measurements east and west of Io observed through a slit	Published (Trafton and Macy, 1978)
	two-dimensional intensity images data	F. J. Murcray (Univ. of Denver; private communication)
Spectral Sodium Data	line profile shapes measured through an observing aperture or slit	J. T. Trauger (Cal. Inst. Tech.; private communication)
	same	Published (Trafton, 1975; Trafton and Macy, 1977)
	same	L. M. Trafton (Univ. of Texas; private communication)

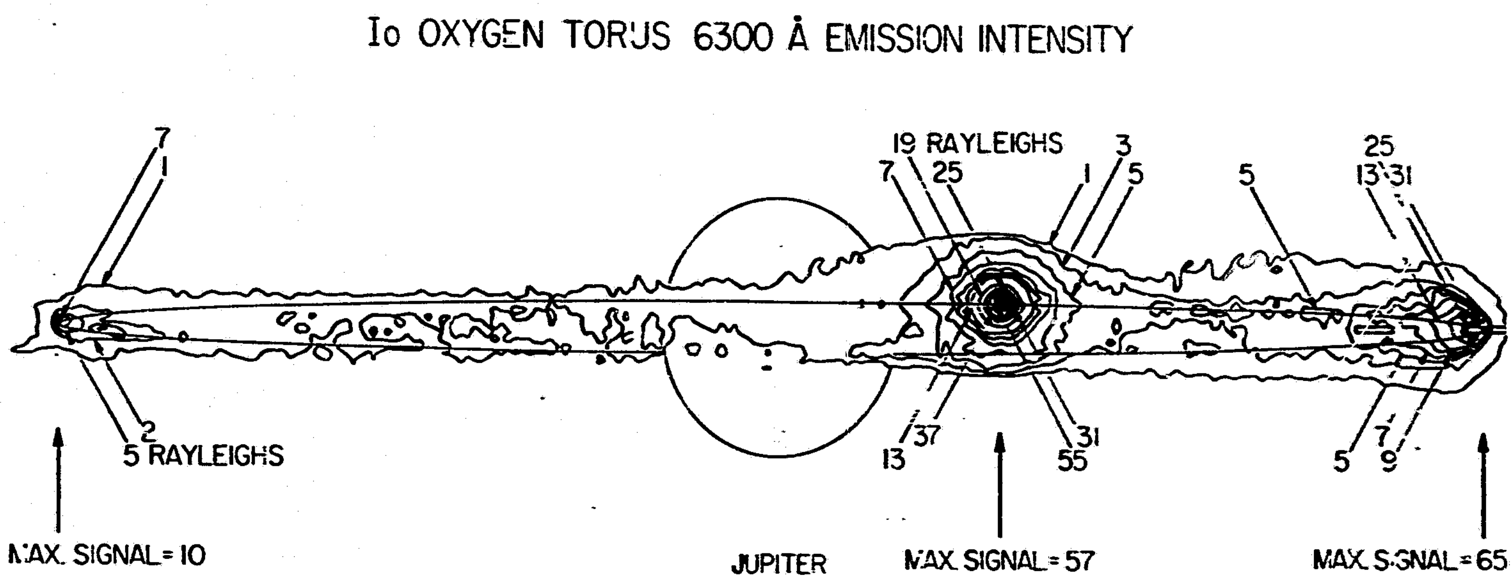

Figure 1

Model results for the 6300Å emission of the Io oxygen cloud are shown at the mid-point of the ground-based observation of Brown (1981). Isotropic emission from Io with a mean speed of 2.6 km/sec and with a satellite surface flux of 10^{10} oxygen atoms $cm^{-2}sec^{-1}$ were assumed in the model calculation. The rectangular observing slit of Brown is also shown to scale at the two positions for which measurements were made.

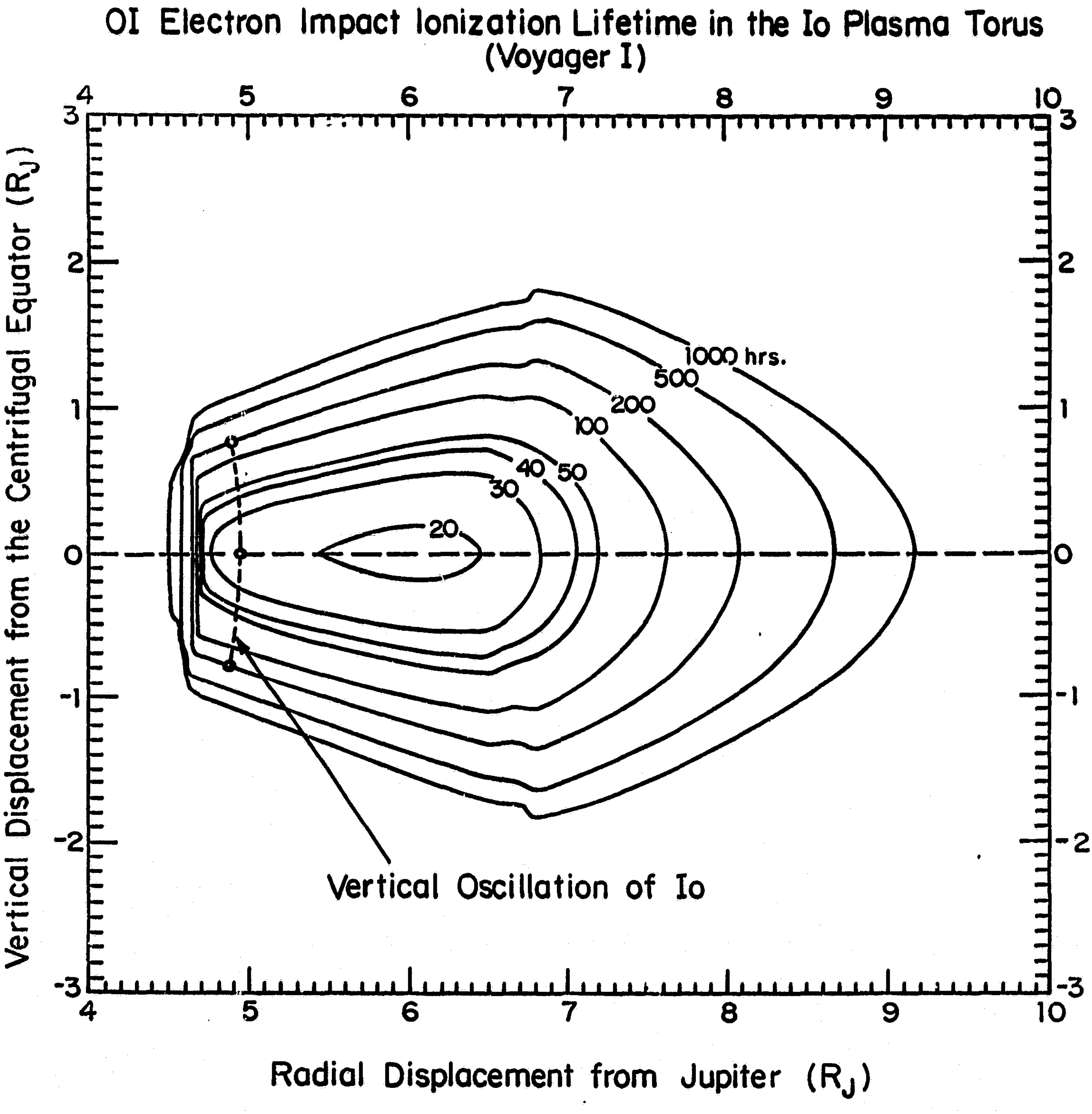

Figure 2

The two-dimensional lifetime of atomic oxygen in the Io plasma torus, calculated for electron impact ionization and assumed in the model results of Figure 1, is shown.

Io: Atomic Oxygen Torus

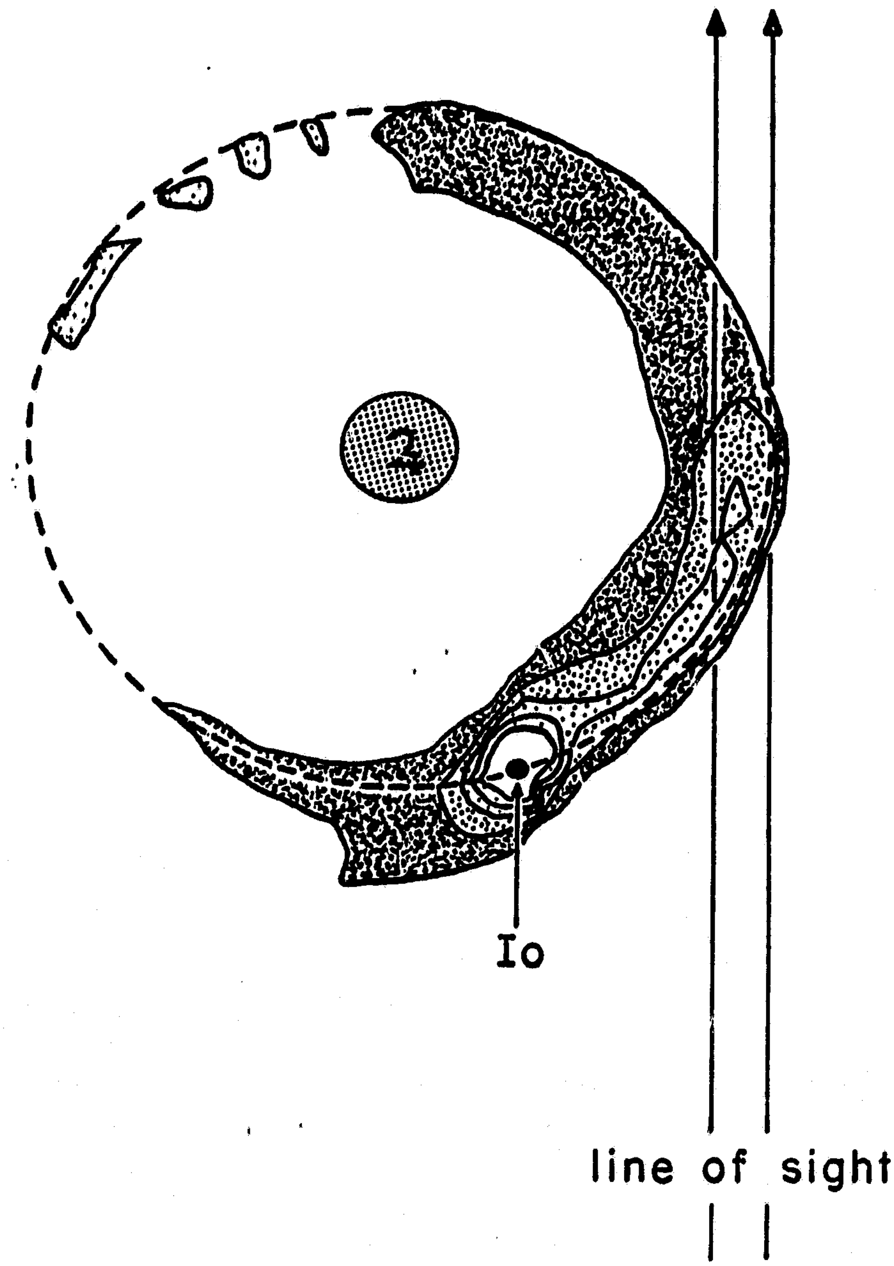

Figure 3

The two-dimensional column density (atoms cm^{-2}) of the Io oxygen cloud is shown as viewed above the satellite plane. Contour values near the satellite are larger.

Io: Oxygen Ion Creation Rate

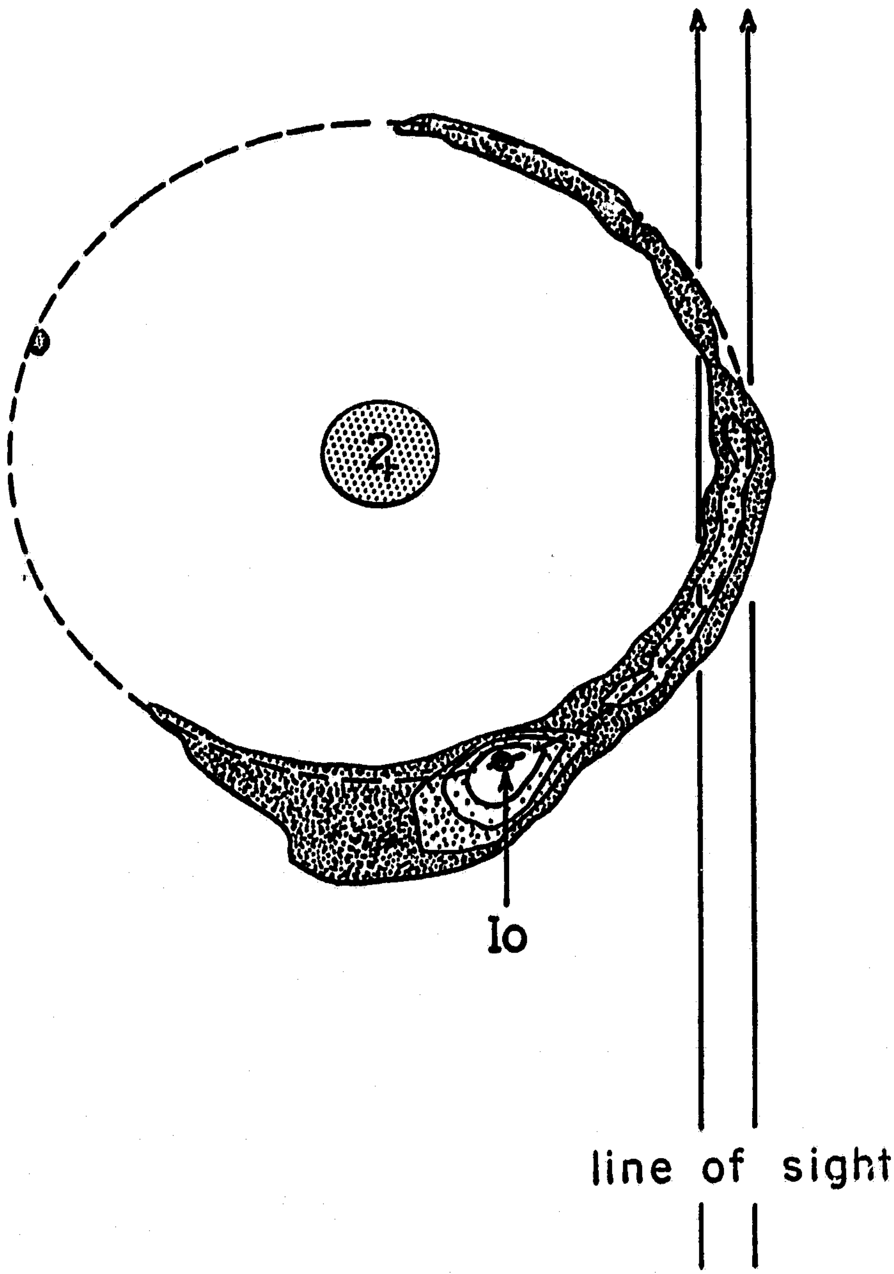

Figure 4

The two-dimensional oxygen ion creation rate (ions $cm^{-2}sec^{-1}$) produced by the interaction of the Io oxygen cloud and the model-assumed non-oscillating plasma torus is shown as viewed from above the satellite plane. Contour values near the satellite are larger.

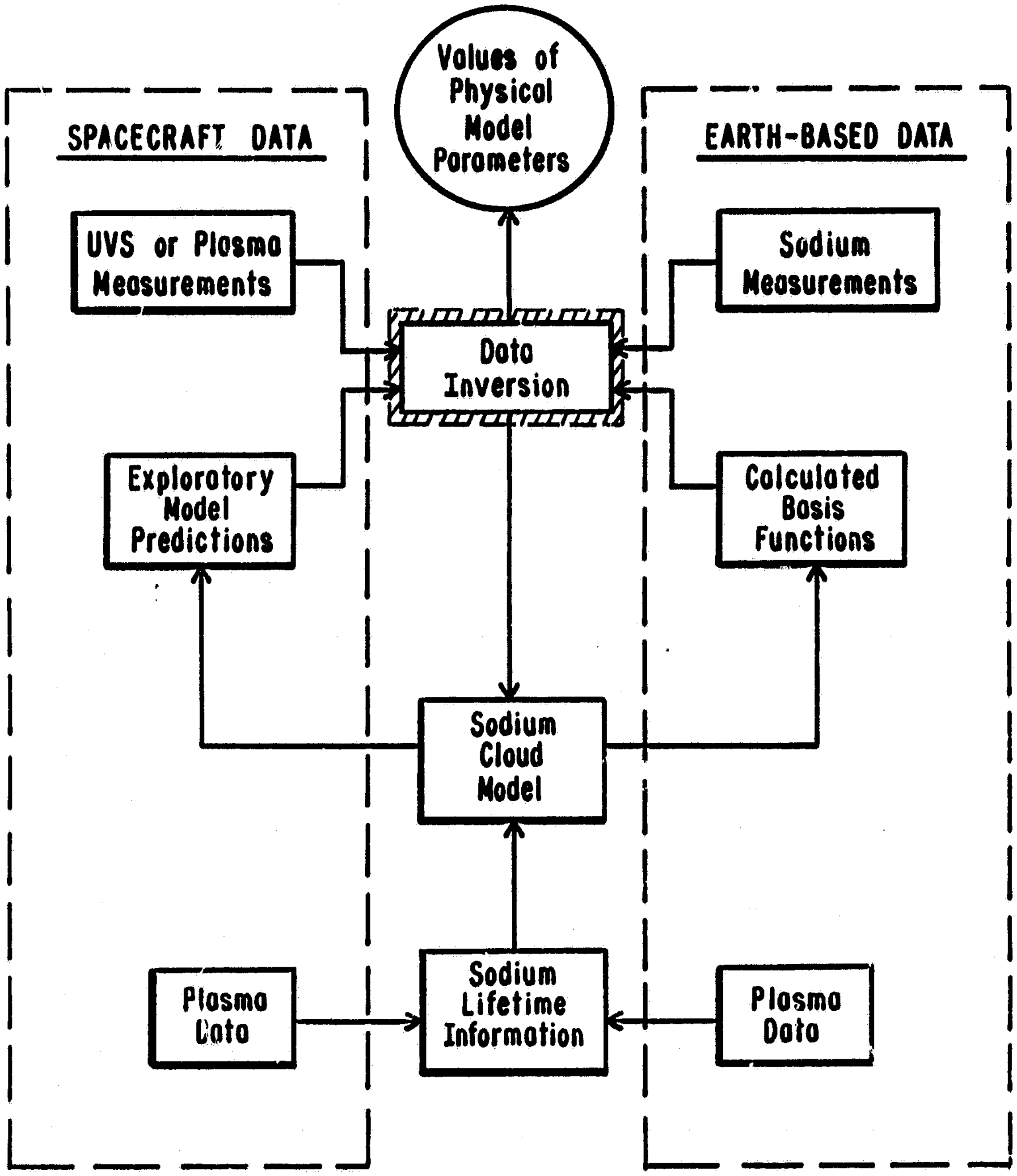

Figure 5

Data Analysis Scheme. The roles of the spacecraft and Earth-based data, the sodium cloud model, and the data inversion technique in determining the values of the physical model parameters are illustrated.

REFERENCES

Bridge, H.S., Belcher, J.W. and Sullivan, J.D. (1981) Private communication.

Brown, R.A. (1981) The Jupiter Hot Plasma Torus: Observed Electron Temperature and Energy Flow. Ap. J. 244, 1072.

Lawson, C.L. and Hanson, R.J. (1974) Solving Least Square Problems. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Mekler, Y.B. (1981) Private communication.

Morgan, J.S. (1981) Density Variations in the Io Plasma Tours. Paper presented at the Physics of the Jovian and Saturnian Magnetospheres Conference, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, October 22-24, 1981.

Nelder, J.A. and Mead, R. (1965) Comp. J., 7, 308.

Pilcher, C.B. and Morgan, J.S. (1981) Private communication.

Pilcher, C.B., Morgan, J.S., Fertel, J.H. and Avis, C.C. (1981) A Movie of the Io Plasma Torus. Presented at the Physics of the Jovian and Saturnian Magnetospheres Conference, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, October 22-24, 1981.

Sandel, B.R. (1981) Discovery of an Io-correlated Energy Source for the Plasma Torus. Paper presented at the Physics of the Jovian and Saturnian Magnetospheres Conference, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, October 22-24, 1981.

Shemansky, D.E. and Sandel, B.R. (1981a) The Injection of Energy to the Io Plasma Torus. Paper presented at the Physics of the Jovian and Saturnina Magnetospheres Conference, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, October 22-24, 1981.

Shemansky, D.E. and Sandel, B.R. (1981b) The Injection of Energy to the Io Plasma Torus. Preprint.

Smith, R.A., Palmadesso, P.J. and Strobel, D.F. (1981) Plasma Wave Induced Energy Transfer in the Io Plasma Torus. Paper presented at the Physics of the Jovian and Saturnian Magnetospheres Conference, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, October 22-24, 1981.

Trafton, L. (1981) Private communication.

Trauger, J.T. (1981a) Private communication.

Trauger, J.T. (1981b) The Jovian [SII]-[SIII] Nebula: Photometry and Line Ratios Based on CCD Imaging. Paper presented at the Physics of the Jovian and Saturnian Magnetospheres Conference, Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, October 22-24, 1981.