



## Jupiter's Ionosphere: Prospects for Pioneer 10

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# Reports

## Jupiter's Ionosphere: Prospects for Pioneer 10

*Abstract. Model Jovian ionospheres are constructed for comparison with Pioneer 10 results. Electron density maxima are predicted at a level approximately 220 kilometers above an assumed reference height where the hydrogen density is  $10^{16}$  molecules per cubic centimeter. It may be possible to use observations of the electron density to locate the turbopause. Attention is drawn to a possible strong source of ionized sodium from Io which might lead to large electron densities at low altitudes.*

Pioneer 10 is scheduled to fly by Jupiter on 3 December 1973 and provide our first closeup view of the giant planet. The mission has multiple objectives, among them to define conditions in Jupiter's upper atmosphere and ionosphere. This report is intended to set the scene for receipt and interpretation of the spacecraft data. We develop a model for Jupiter's ionosphere, including all known relevant chemical reactions. We explore the dependence of the model on various uncertain parameters, offering a yardstick against which one may judge the significance of the new data.

Jupiter's atmosphere consists mainly of  $H_2$  and He, with trace quantities of  $CH_4$  and  $NH_3$ . The mixing ratio of He is  $0.26^{+0.16}_{-0.21}$  according to a recent analysis of data obtained during the occultation of Beta Scorpii by Jupiter (1). The mixing ratio for  $CH_4$  is  $7 \times 10^{-4}$ , and the abundance of  $NH_3$  is too small for this gas to play any role in the present study (2). The upper atmosphere is expected to contain important quantities of H formed by dissociation of  $H_2$  and  $CH_4$ , and the composition of the upper atmosphere is affected by the strength of turbulent mixing assumed to occur at lower levels.

*Scoreboard for Reports:* In the past few weeks the editors have received an average of 68 Reports per week and have accepted 12 (17 percent). We plan to accept about 12 reports per week for the next several weeks. In the selection of papers to be published we must deal with several factors: the number of good papers submitted, the number of accepted papers that have not yet been published, the balance of subjects, and length of individual papers.

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Strobel (3) derived a value of  $2 \times 10^4$   $cm^2$   $sec^{-1}$  for the eddy diffusion coefficient in the lower stratosphere from a consideration of the ultraviolet albedo of Jupiter. Wallace and Hunten (4) placed an upper limit of  $10^6$   $cm^2$   $sec^{-1}$  on the eddy diffusion coefficient at the turbopause from an interpretation of the Lyman-alpha albedo measured by Moos and Rottman (5). Interpretation of the Lyman-alpha data may be confused, however, by a possible contribution to the observed flux due to scattering in a toroid of gas near Io's orbit (6). We regard the eddy coefficient as still undetermined, and accordingly consider it as a parameter to be varied in this analysis and, we hope, to be determined by the Pioneer data.

The sources of ionization associated with absorption of sunlight are reviewed by McElroy (2), and his analysis is followed here. We emphasize particularly the role of dissociative photoionization of  $H_2$ , which offers an important source of  $H^+$  ignored in previous models.

The chemical model is summarized in Table 1; several reactions merit special comment. Protons are removed by the three-body reaction e6 over an extensive height range (7). Helium ions are most probably lost by a combination of e3 to e5, although the associated rate constants have not been measured. The ion  $HeH^+$  can be removed by either e7 or r3, with e7 dominant at all heights of interest here. Reactions e6 and e7 were omitted in most previous models for Jupiter's ionosphere, which resulted in major overestimates for the concentrations of  $H^+$  and  $HeH^+$ . Reactions e6 and e7 provide important sources of  $H_3^+$ . The rate constant for r1 is larger, by a factor of 40, than values used earlier

(8). The electron density at lower altitudes is reduced accordingly.

A model ionosphere is shown in Fig. 1. We adopted an eddy diffusion coefficient of  $10^5$   $cm^2$   $sec^{-1}$  and assumed a mixing ratio of 0.24 for He in the lower atmosphere. The height scale was arbitrarily normalized to a zero reference value at a level where the atmospheric density was  $10^{16}$  molecules per cubic centimeter. The turbopause for He is at 60 km. Densities of H were obtained by numerical solution of the appropriate diffusion and continuity equations (2).

The dominant ion above about 180 km is  $H^+$ . At lower altitudes  $H_3^+$  is dominant, in contrast with the earlier work where  $H^+$  was the major component at all altitudes. The maximum concentration of  $H_2^+$  is at 400 km with a value  $2.2$   $cm^{-3}$ . The peak concentration of  $He^+$  is at 100 km with a value  $1.3 \times 10^{-1}$   $cm^{-3}$ , and the concentration of  $HeH^+$  is vanishingly small, less than  $10^{-5}$   $cm^{-3}$ , at all altitudes.

The dependence of results on the assumed magnitude of the eddy mixing coefficient,  $K$ , is illustrated in Fig. 2. An increase in  $K$  leads to a decrease in the computed values for the concentration of H, with a corresponding reduction in the source of  $H^+$  associated with direct photoionization of H. Increased mixing, however, leads to an increased concentration of He at any level above the turbopause. As a consequence, e5 becomes important as a source of  $H^+$ . The large increase in the computed value for electron density at the ionospheric maximum in the model with  $K = 10^8$   $cm^2$   $sec^{-1}$  can be directly attributed to e5 and may provide an indirect means for determination of the eddy diffusion coefficient. The effect is masked by the efficient reaction e6 in the curves with  $K$  equal to  $5 \times 10^6$  and  $10^5$   $cm^2$   $sec^{-1}$ . The magnitude of the effect is relatively insensitive to the rate constant,  $K$ , assumed for total reaction of  $He^+$  with  $H_2$ , reactions e3 to e5. It does, however, depend rather critically on the branching ratio  $k_5/(k_3 + k_4 + k_5)$ . In this study we assumed equal rates for e3 to e5. Laboratory data are urgently required in order to define the relative roles of these reactions.

A recent observation of intense emission from Io in the D lines of atomic sodium (9) has led to the suggestion (6) that Io may have an atmosphere containing significant quantities of nitrogen, hydrogen, and sodium. Nitro-

gen and hydrogen are supplied by photolysis of ammonia, released by evaporation from a layer of surface ice containing dissolved sodium. Gases readily escape Io, forming a toroid around Jupiter. They are eventually ionized and swept up by Jupiter's magnetic field, forming a potential source of trapped radiation, which must ultimately dissipate and enter Jupiter's atmosphere. Io could supply a flux of nitrogen and hydrogen ions as large as  $6 \times 10^7 \text{ cm}^{-2} \text{ sec}^{-1}$  averaged over the entire surface of Jupiter, and the flux at high latitudes could be much larger than this value, perhaps by a factor as large as  $10^3$ . Fluxes of sodium ions are less well determined, although the planetary average flux at Jupiter is not likely to be much less than  $10^5 \text{ cm}^{-2} \text{ sec}^{-1}$ . Ionization from these Io-related sources could represent a major perturbation for the ionospheric models presented in this report. It would be particularly difficult to remove sodium ions in the Jovian environment. There are no obvious ion-molecule reactions between  $\text{Na}^+$  and major components of Jupiter's atmosphere. Radiative recombination could provide the sole loss mechanism down to a level at which three-body reactions become important. The rate constant for three-body recombination should be of the order  $10^{-27} \text{ cm}^6 \text{ sec}^{-1}$  (10). Sodium ions could survive, therefore, with appreciable density down to a level at which the neutral background density had a value of about  $10^{15} \text{ cm}^{-3}$ ; that is, to an altitude of about 40 km, according to the height scale in Figs. 1 and 2.

The possible presence of sodium as a trace component of Jupiter's atmo-

Table 1. Important reactions in the Jovian ionosphere. The rate constants are in units of  $\text{cm}^3 \text{ sec}^{-1}$  for two-body reactions and  $\text{cm}^6 \text{ sec}^{-1}$  for three-body reactions.

Reaction number	Reaction	Rate constant	Reference
<i>Ion production</i>			
p1	$\text{H}_2 + h\nu \rightarrow \text{H}_2^+ + e$		
p2	$\text{H}_2 + h\nu \rightarrow \text{H}^+ + \text{H} + e$		
p3	$\text{H}_2 + e \rightarrow \text{H}_2^+ + 2e$		
p4	$\text{H}_2 + e \rightarrow \text{H}^+ + \text{H} + 2e$		(2)
p5	$\text{H} + h\nu \rightarrow \text{H}^+ + e$		
p6	$\text{H} + e \rightarrow \text{H}^+ + 2e$		
p7	$\text{He} + h\nu \rightarrow \text{He}^+ + e$		
p8	$\text{He} + e \rightarrow \text{He}^+ + 2e$		
<i>Ion exchange</i>			
e1	$\text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H}$	$\sim 5 \times 10^{-10}$	(14)
e2	$\text{H}_2^+ + \text{H} \rightarrow \text{H}_2 + \text{H}^+$	$\sim 1 \times 10^{-10}$	(14)
e3	$\text{He}^+ + \text{H}_2 \rightarrow \text{He} + \text{H}_2^+$	} sum $< 1 \times 10^{-13}$	(15)
e4	$\text{He}^+ + \text{H}_2 \rightarrow \text{HeH}^+ + \text{H}$		
e5	$\text{He}^+ + \text{H}_2 \rightarrow \text{He} + \text{H} + \text{H}^+$		
e6	$\text{H}^+ + \text{H}_2 + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H}_2$	$3.2 \times 10^{-20}$	(16)
e7	$\text{HeH}^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{He}$	$1.85 \times 10^{-9}$	(17)
<i>Ion removal/electron-ion recombination</i>			
r1	$\text{H}_3^+ + e \rightarrow \text{H}_2 + \text{H}$	$3.8 \times 10^{-7}$	(8)
r2	$\text{H}_2^+ + e \rightarrow \text{H} + \text{H}$	$< 1 \times 10^{-8}$	(14)
r3	$\text{HeH}^+ + e \rightarrow \text{He} + \text{H}$	$\sim 1 \times 10^{-8}$	(14)
r4	$\text{H}^+ + e \rightarrow \text{H} + h\nu$	$6.6 \times 10^{-12}$	(18)
r5	$\text{He}^+ + e \rightarrow \text{He} + h\nu$	$6.6 \times 10^{-12}$	(18)

sphere was discussed by Wildt (11). He drew attention to the potential importance of sodium in solution with ammonia as a coloring agent for Jupiter's clouds. The density of sodium ions in equilibrium with atomic sodium would be given approximately (6) by  $Ne^2 = 10^5[\text{Na}]$  in the region where radiative recombination was the dominant loss mechanism; here  $Ne$  defines the electron density, taken to be equal to the density of  $\text{Na}^+$ , and  $[\text{Na}]$  is the density of neutral Na. If we consider the source of Na associated with Io, and adopt Strobel's (3) estimate for the eddy mixing coefficient, we can estimate a value for the stratospheric density of neutral Na on Jupiter. We calculate a concentration of  $10^7 \text{ cm}^{-3}$ ,

sufficient sodium to supply a low-altitude ionization layer with a density of the order of  $10^6 \text{ cm}^{-3}$ . Larger values could apply if Jupiter has an intrinsic source of Na.

We have attempted to give some estimates of the probable characteristics of an ionosphere which might be detected on Jupiter by Pioneer 10. We have omitted sources of ionization associated with auroral activity, although several electrodynamic models (12) describing the coupling of Jupiter to Io would suggest that aurorally related ionization could be at least locally important. Pioneer 10 offers the prospect for new insights into the physical and chemical processes which regulate conditions in Jupiter's upper atmosphere.

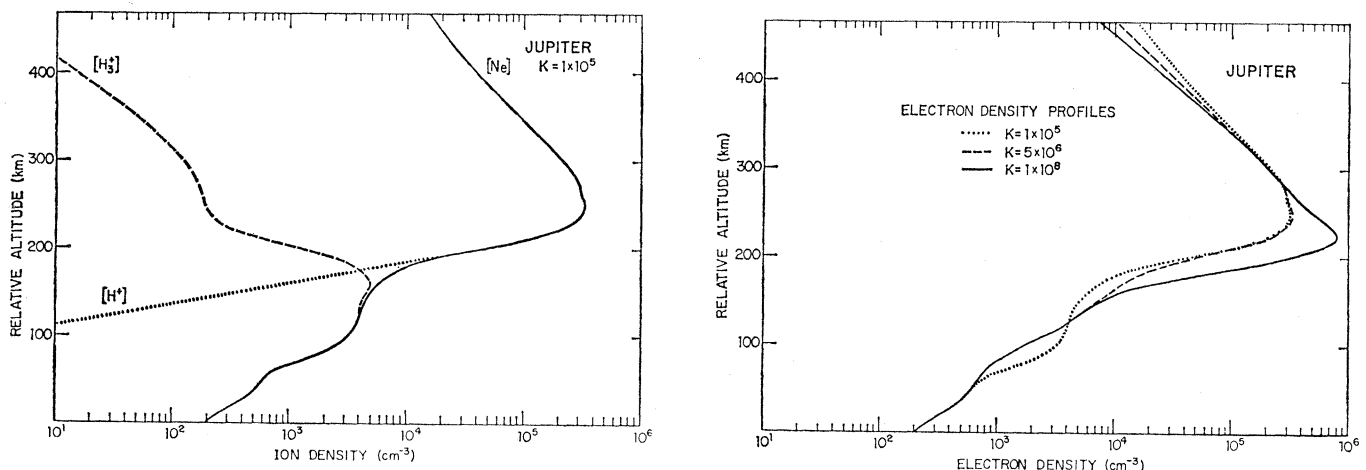


Fig. 1 (left). Model for Jupiter's ionosphere with eddy diffusion coefficient  $K = 1 \times 10^5 \text{ cm}^2 \text{ sec}^{-1}$  and He mixing ratio 0.24. The maximum computed values of the  $\text{HeH}^+$ ,  $\text{He}^+$ , and  $\text{H}_2^+$  densities are very low and cannot be drawn on the scale of this figure. Fig. 2 (right). Models for the electron density in Jupiter's ionosphere with eddy diffusion coefficients  $K = 1 \times 10^5$ ,  $5 \times 10^6$ , and  $1 \times 10^9 \text{ cm}^2 \text{ sec}^{-1}$  and He mixing ratio 0.24.

Major surprises and departures from the models developed here may occur, and indeed might be expected on the basis of earlier experience. Theoretical models for the martian ionosphere failed totally to account for the initial data obtained by Mariner 4 (13). If the models for Jupiter suffer a similar fate at the hands of Pioneer 10, we may look forward to an exciting era in an expanded arena of planetary aeronomy.

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## Sulfuric Acid-Ammonium Sulfate Aerosol: Optical Detection in the St. Louis Region

**Abstract.** *Nephelometric sensing of the deliquescence of ammonium sulfate produced by the reaction of sulfuric acid or ammonium bisulfate aerosol with ammonia provides a means for detecting these substances in air. Field experiments show them to be the dominant substances in the submicrometer, light-scattering aerosol in the St. Louis region.*

Atmospheric  $H_2SO_4$  aerosol, present as droplets of the acid and its products of neutralization with  $NH_3$  mixed with other substances, have proved to be difficult to detect and quantify by traditional air-sampling methods (1). Knowledge of the existence of these compounds is important for an understanding of the natural sulfur cycle, atmospheric optics, acid rain, and health effects due to air pollution. Almost all the sulfate data in existence today are for the anion alone and provide no information regarding the attached cation. Nonetheless, the important properties of sulfates (toxicity, water solubility, refractive index, particle state and shape, and acidity) depend on the molecular composition and not on the anion alone. The recent CHES (Community Health and Environmental Surveillance System) report (2), linking  $SO_4^{2-}$  with effects on health, cannot be adequately understood unless the molecular forms of the compounds are known. Furthermore, control of the  $SO_4^{2-}$  may depend on the molecular form.

Not least among the analytical problems is the reactivity of  $H_2SO_4$  with

or on sampling surfaces and with  $NH_3$  to which the sample is probably exposed when handled. As a result, it is attractive to consider in situ methods of analysis which do not require the removal of particles from the air.

Our purposes in this report are to describe a method for sensing aerosols of  $H_2SO_4$ ,  $NH_4HSO_4$ , and  $(NH_4)_2SO_4$  and to present atmospheric data taken in and near St. Louis, Missouri. The basic apparatus, a humidograph (3), measures the dependence of the light-scattering coefficient of the particulate matter ( $b_{sp}$ ) on the relative humidity (RH). This system can be operated with the injection of a few parts per million of  $NH_3$  into the sample flow, causing the reaction of  $H_2SO_4$  and  $NH_4HSO_4$  to form  $(NH_4)_2SO_4$ . Both  $H_2SO_4$  and  $NH_4HSO_4$  aerosols exhibit a monotonic humidogram (the curve of light scattering versus humidity) in which  $b_{sp}$  increases continually with increasing RH as a result of the hygroscopic nature of these materials. The  $(NH_4)_2SO_4$  humidogram, however, has an inflection point at about 80 percent RH owing to its deliquescent property (4). Aerosol particles of a deliquescent salt remain

Table 1. Effect of  $NH_3$  addition on the ambient air humidogram.

Category	Location and date			
	Tyson Hollow, 21 to 27 September 1973 (88 pairs of measurements)*		St. Louis University, 27 September to 2 October 1973 (258 pairs of measurements)*	
	Number of mea- surements	Percent- age of total	Number of mea- surements	Percent- age of total
Category A: Monotonic before addition of $NH_3$ ; $NH_3$ caused an inflection at about 80 percent RH	46	52	22	8.5
Category B: Inflection at about 80 percent RH prior to $NH_3$ addition; $NH_3$ enhanced the inflection	22	25	5	1.9
Category C: Inflection at 80 percent RH; no change with $NH_3$ addition	19	22	64	24.8
Category D: Monotonic curve; no effect with $NH_3$ addition	1	1	167	64.8

\* Not all measurements are included here owing to the fact that a measurement of the effect of the addition of  $NH_3$  was not carried out after each ambient measurement.