Reports

Atomic Clouds as Distributed Sources for the Io Plasma Torus

Abstract. *Several recent developments have implications for the neutral particle environment of Jupiter. Very hot sulfur ions have been detected in the Io torus with gyrospeeds comparable to the corotation speed, a phenomenon that would result from a neutral sulfur cloud. Current evidence supports the hypothesis that extensive neutral clouds of oxygen and sulfur exist in the Jupiter magnetosphere and that they are important sources of ions and energy for the Io torus.*

Flows of heavy-element ions are observed to dominate the composition and physical state of Jupiter's charged particle environment. Observations of the thermal plasma span less than a decade, including the four Pioneer and Voyager snapshots plus the continuing optical and ultraviolet line emission studies from ground-based and Earth-orbiting stations (*1, 2*). These studies provide insight into the physical processes that sustain robust flows of particles and energy in a complex geophysical system.

There are two unresolved basic issues concerning the dynamics and structure of the Io torus of oxygen and sulfur ions: (i) the source location for these heavy ions and (ii) the process that supplies energy for the observed optical and ultraviolet emissions. These are the starting points for modeling the ion spatial distribution and balancing the plasma energy budget. We are led by diverse lines of reasoning to the view that Io's extensive neutral atom cloud may be the dominant source of ions and energy. Here we review the existing evidence and report a new observation of a very hot plasma ion component that is consistent with ionization of cloud atoms.

After detection of the sulfur nebula through the observation of optical emissions from collisionally excited S II (*3*), it was suggested (*4*) that the energy could be supplied from thermalization of extremely hot, newly created ions. Extensive clouds of alkali metal atoms were known to exist near Io (*5, 6*). Ionization of such atoms by photoionization, charge exchange, or electron impact would produce hot ions gyrating with a speed similar to the relative motion of the ballistic atoms and the corotating plasma (57 km sec^{-1} at Io's orbit). The associated kinetic energy would be available to the plasma electrons, which excite the emissions responsible for plasma energy loss.

The apparent absence of high-speed S$^+$ (*7*) and a reported large plasma scale height (*3*) were interpreted by Eviatar *et al.* (*8*) as indicating a large temperature anisotropy in plasma heavy ions. They suggested that the low energy perpendicular to the magnetic field implied that the ions were created in a magnetically shielded region at Io; the high parallel temperature was taken as an artifact of ion injection over the range of magnetic latitudes sampled by Io's orbit (*9*). Eviatar *et al.* (*8*) argued for a low-density, low-mass plasma (~ 500 cm^{-3}), which would preserve this temperature anisotropy by reducing the importance of collisions.

These three inferences have been found to be incorrect. We report here the detection of ions with gyrospeeds near the corotation speed. Parallel and perpendicular temperatures do vary with position in the plasma, but retain isotropy (*1*). The plasma is dense: charge densities in the range 2×10^3 to 5×10^3 cm^{-3}, observed in optical studies by Brown (*10, 11*), have been generally confirmed by measurements in situ (*12, 13*). Collisions are important for the Jovian plasma, and there is no remaining kinematic requirement for an ion source completely localized at Io.

The hot-ion power mechanism was raised again by the Voyager ultraviolet spectrometer experiment (*14*). Since sulfur and oxygen atoms would yield about 540 and 270 eV per ionization, respectively, the observed total emission rate of 2×10^{12} to 3×10^{12} W (*15*) implies a total ionization rate of about 4×10^{28} sec^{-1} for a sulfur-to-oxygen ratio of 0.5. But a population of sulfur and oxygen neutral atoms away from Io was not established by Voyager, and the required production rate exceeded by three orders of magnitude the visible production rate of sodium ions from the parent atomic cloud (*16, 17*).

New evidence for hot ions resulting from ionization of cloud atoms. The apparent absence in spectral observations of a hot-ion component has been taken to indicate a lack of newly created ions and hence the relative unimportance of atom clouds as an ion source. However, there is an observational bias favoring cooler distributions in energy- or velocity-dispersive detection: the signal from a hot component is spread out relative to the concentrated response to a cool component. This is illustrated in Fig. 1, a spectrum of the 6716- and 6731-Å features of S II at the eastern elongation of Io's orbit. The emission line is much broader than the instrumental line profile, hence its shape is an approximate map of the distribution of ion line-of-sight velocities. A single Maxwellian distribution (temperature $T_\perp \simeq 16$ eV) fits the line core but not the wings, which are satisfactorily described by an ~ 360-eV component containing about one-third the total S$^+$ density.

The broadening of a spectral line is commonly described by a measured width, and the interpretation invokes some physical mechanism to predict a theoretical line shape, from which the width alone is extracted for comparison with observation. This procedure discards information if the observed and theoretical line profiles differ, which is true in the present case. The Jovian S II emission line is not well described by a single-temperature Doppler line profile. While nothing detailed can be said about the distribution of high-speed ions at this point, their existence is required by the spectrum in Fig. 1.

This result agrees with the suggestion by Bagenal and Sullivan (*18*) that a very high-energy pseudo-continuum with a high-speed cutoff may underlie some of the Voyager plasma science experiment spectra; that is the expected signature of newly created ions. The disappearance of this indication of new ions outside 6 Jupiter radii (R_J) may again be due to lower detectability in the presence of that region's high plasma temperatures. Intriligator and Miller (*19*) recently found occasional high-energy tails in a reexamination of the Pioneer 10 plasma analyzer data.

Existing evidence for major neutral atom clouds. Brown (*20*) detected an atomic oxygen cloud by faint emission at 6300 Å. The estimated oxygen density of 30 cm^{-3} implies a source of ~ 10^{28} sec^{-1}. There is uncertainty about both the volume and lifetime of the neutral oxygen, and the supply rate estimate is proportional to their ratio. However, the atom partial torus grows in longitudinal extent

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with time (*21*). Therefore, the production rate result is insulated from these uncertainties to first order.

The total atomic supply rates can be estimated from the plasma mixing ratios of constituents that are observed in atomic clouds, but only under the assumption of a common cloud origin for all species. The Voyager plasma science experiment found 1 to 10 percent for Na and 17 to 25 percent for O (*18*), implying total sources of order $10^{28 \pm 0.7}$ sec^{-1} (from Na) and 3×20^{28} sec^{-1} (from O). Thus, optical observations of the detected neutral species imply similar values of the total neutral production rate.

In situ measurements of energetic charged particles in the Jovian magnetosphere also provided information on the neutral atomic clouds. The probable detection of energetic neutral particles ejected from the Jovian system was reported by Kirsch *et al.* (*22*). The corresponding loss rate for the 14- to 31-keV particles is $< 10^{25}$ sec^{-1}. Following Cheng (*23*), Kirsch *et al.* suggested that these energetic neutrals were produced by charge exchange reactions between inwardly diffusing charged particles and atoms in the Io neutral clouds.

In a study of the pitch angle distributions of ions detected by the low-energy charged particle experiment on Voyager 1, Lanzerotti *et al.* (*24*) also found evidence supporting the charge exchange process. These distributions for particles with energies of 1.05 to 2.0 MeV are pancake-like outside the orbit of Io but dumbbell-shaped at 5 R_J, with a significant reduction in the particles mirroring at low magnetic latitudes. As pointed out by Cheng (*23*), such a pitch angle–dependent effect in charged particle loss is expected from the charge exchange process. From a consideration of the radial diffusion and loss of the magnetospheric particles between 5 and 8 R_J, Ip (*25*) finds a number density of $\lesssim 180$ cm^{-3} for neutral oxygen and sulfur atoms in the vicinity of Io's orbit, consistent with the number density obtained by Brown (*20*) from optical observations.

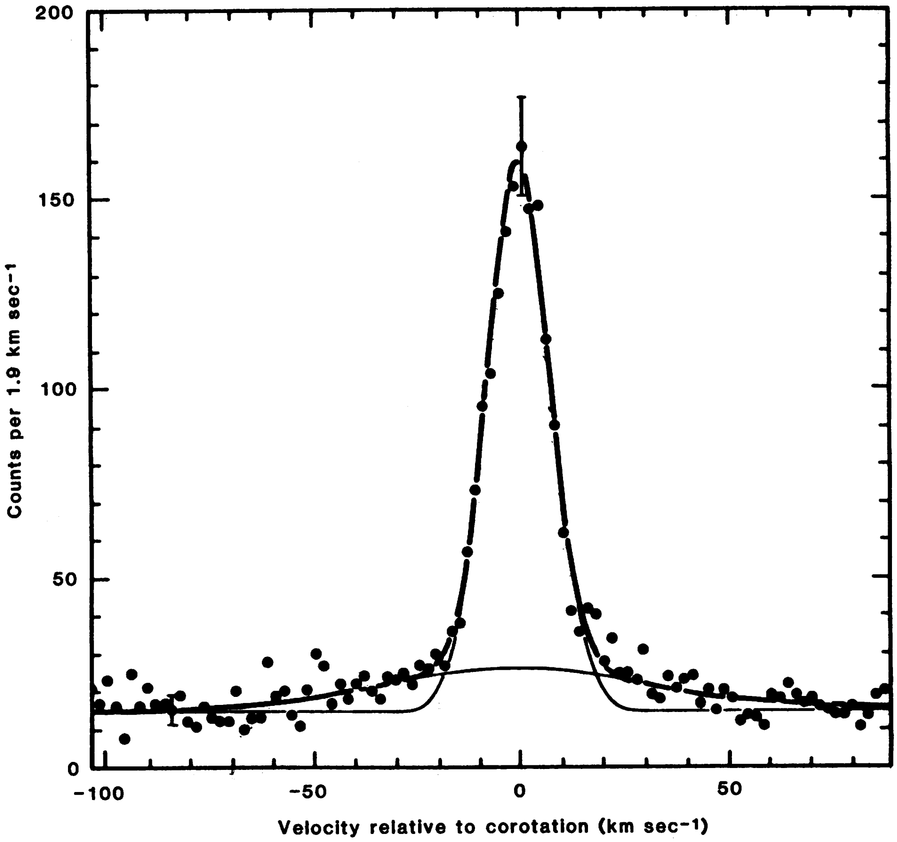

Fig. 1. Spectrum of S II emission from the Io torus. The points are a combination of the recorded photons in the 6716- and 6731-Å features: the two line centers have been overlapped and the responses summed. The Doppler relation was used to produce the velocity scale from a detailed wavelength dispersion solution of a comparison lamp spectrum. The faint curves show Maxwellian gyrospeed distributions with kinetic temperatures of 16 and 360 eV, which separately fit the line core and wings. The bold curve is a sum of the cold and hot components, weighted, respectively, by 71 and 29 percent of the total light. The observation was made by R.A.B. on 24 February 1981, 11:24 to 11:39 UT, using the 60-inch (1.5-m) telescope of the Smithsonian Astrophysical Observatory near Tucson, Arizona. The spectrograph was a Cassegrain echelle with an approximately Gaussian instrumental profile of 0.17 Å full width at half-maximum (equivalent S^+ temperature, 3.4 eV). The detector, a Reticon array preceded by a cooled image intensifier (*35*), recorded individual photoelectron events. The slit measured 6.7 by 0.3 arc second or 0.3 by 0.02 R_J projected on the sky. It was positioned 5.9 R_J east of Jupiter's center in the plane of the satellite orbits; the long slit dimension was oriented east-west on the celestial sphere.

Besides influencing the lossy diffusion of the magnetospheric charged particles, the charge exchange process enhances the hot-ion power mechanism by increasing the ionization rate. The net effect is substitution of hot new ions with a gyroenergy of a few hundred electron volts for the cold ions with a thermal energy of a few electron volts. This is particularly important for the region of the cold S II nebula inside 6 R_J, where most of the particles are singly ionized and the cooler electrons are less efficient in causing ionization. Using the electron-capture cross sections between S and O atoms and ions given by Kunc and Judge (*26*), we estimate that the average lifetime of S^+ and O^+ against charge exchange loss is about 4×10^5 seconds if the neutral number density is on the order of 50 cm^{-3}. With a neutral cloud volume of 4×10^{30} cm^3 and an average plasma ion density of 10^3 cm^{-3}, the corresponding ion loss rate would be $\sim 10^{28}$ sec^{-1}. The charge exchange ionization rate of the neutral atoms would be the same.

Cummings *et al.* (*27*) suggest that electron density irregularities detected by the Voyager 1 radio astronomy experiment were caused by fresh plasma oscillating in magnetic latitude following ionization away from the equilibrium latitude. This requires a displacement away from Io of the centroid of plasma creation, implying a distributed neutral atom source.

Discussion. The factors favoring distributed neutral clouds do not rule out the ionosphere of Io as a source of the torus plasma. There is, however, little evidence that it is the dominant source. One estimate, which relates the field-aligned current across Io to the pickup of ionospheric mass, yields an ion production rate of about 10^{28} sec^{-1} (*28–30*). However, in a study of the Voyager ultraviolet data, Shemansky (*31*) reported an upper-limit production rate of 10^{27} sec^{-1} in the vicinity of Io. Io may eject large amounts of ionized gas into the magnetosphere episodically, but the steady source of the extended neutral clouds is probably dominant in maintaining the Io torus.

Heating mechanisms other than assimilation of new ions may supply power to the Io plasma torus. For example, wave-particle interactions could be important in determining the detailed velocity distributions of heavy ions and the global thermal structure of the torus [for example, see (32)]. The relative importance of different heating and cooling effects [that is, fast thermalization of hot ions through collective plasma processes (33, 34) versus energy transfer through ion-ion and electron-ion Coulomb collisions] must be evaluated in connection with the analysis of spectral data exemplified in Fig. 1.

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Acetylcholine Synthesis in Synaptosomes: Mode of Transfer of Mitochondrial Acetyl Coenzyme A

Abstract. *Labeled acetylcholine derived from labeled pyruvate in a synaptosomal preparation from rat brain, incubated with nicotinamide adenine dinucleotide as well as coenzyme A, is stimulated by calcium ions in the absence but not in the presence of Triton X-100. Whereas citrate is taken up by cholinergic synaptosomes because it suppresses the formation of acetylcholine from pyruvate, it is not itself converted into acetylcholine. The evidence suggests that there is a calcium-dependent transfer of mitochondrial acetyl coenzyme A into the cholinergic synaptoplasm, which is apparently devoid of the citrate cleavage enzyme, and is there converted into acetylcholine. The permeability of the inner mitochondrial membrane to coenzyme A and acetyl coenzyme A seems to be enhanced by calcium ions, and this effect may be mediated by mitochondrial phospholipase* A_2.

An outstanding question in neurochemistry is how acetyl coenzyme A (CoA) originating in the mitochondria enters the cholinergic cytoplasm, where it is converted into acetylcholine. The inner mitochondrial membrane has been held to be largely impermeable to acetyl CoA (*1*). Various proposals have been made: (i) the conversion of mitochondrial acetyl CoA into citrate that enters the cytoplasm where the citrate cleavage enzyme, adenosine triphosphate (ATP) citrate lyase (E.C. 4.1.3.8), forms acetyl CoA and oxaloacetate (*2*); (ii) the presence in cholinergic nerve terminals of soluble, extramitochondrial pyruvate dehydrogenase (*3*); and (iii) the transfer of sufficient acetyl CoA across the mitochondrial barrier to supply all the brain acetylcholine (*4*, *5*). These and other proposals have been reviewed (*5*, *6*).

We report that the cholinergic synaptoplasm is apparently almost devoid of the citrate cleavage enzyme. Our evidence also indicates that acetyl CoA emanates as such from the cholinergic mitochondria by a calcium-dependent mechanism and that the outflow is much facilitated by phospholipase A_2. It has been suggested that acetyl CoA may

Table 1. The synthesis of [^{14}C]acetylcholine ([^{14}C]ACh) from [^{14}C]pyruvate and [^{14}C]citrate in crude synaptosomal fractions of rat brain in the presence and absence of Triton X-100. A crude synaptosomal fraction (3 to 5 mg of protein) was incubated aerobically for 1 hour at 37°C in 3 ml of incubation medium of the following composition: KCl, 100 m*M*; $MgSO_4$, 1.3 m*M*; choline, 5 m*M*; eserine, 0.4 m*M*; Na_2HPO_4, *p*H 7.4, 10 m*M*; and sucrose, 53.3 m*M*. Further additions of NAD (1 m*M*); EGTA (3 m*M*); $CaCl_2$ (1 m*M*); CoA (0.1 m*M*); sodium citrate (2 m*M*); sodium succinate (2 m*M*), sodium oxaloacetate (2 m*M*); amobarbital (1 m*M*); and Triton X-100 (0.12 percent) were made. Labeled precursors (Amersham), sodium pyruvate (5 m*M*), or sodium citrate (5 m*M*), had activities of 0.5 μCi per vessel. Each result is the mean of at least four determinations ± 1 standard deviation; N.M., not measurable.

Additions	[^{14}C]ACh (nanomoles per 100 mg of protein per hour)	
	No Triton	With Triton
	With [2-^{14}C]pyruvate	
NAD and Ca^{2+}	48 ± 5*	737 ± 23†
NAD and CoA	61 ± 10*	2300 ± 100‡
NAD, Ca^{2+}, and CoA	203 ± 8	1988 ± 99*
Ca^{2+}	53 ± 5*	
Ca^{2+} and CoA	85 ± 5	74 ± 14†
Ca^{2+}, CoA, and amobarbital	55 ± 6§	
NAD, Ca^{2+}, CoA, and amobarbital	247 ± 16‖	1961 ± 110
NAD, Ca^{2+}, CoA, and oxaloacetate	31 ± 4*	115 ± 30†
NAD, Ca^{2+}, CoA, and succinate	69 ± 12*	1775 ± 49‡
NAD, Ca^{2+}, CoA, and citrate	121 ± 5*	1780 ± 95‡
EGTA	26 ± 5*	
NAD and EGTA	41 ± 7*	
NAD, EGTA, and CoA	35 ± 3*	2463 ± 82†
NAD, Ca^{2+}, CoA, and EGTA	42 ± 9*	
	With [1, 5-^{14}C]citrate	
None	N. M.	332 ± 18†
Oxaloacetate	N. M.	71 ± 20†
ATP	N. M.	394 ± 22
NAD and CoA	N. M.	464 ± 20
NAD, CoA, and Ca^{2+}	N. M.	470 ± 17

* $P < .001$ with respect to the control (NAD, Ca^{2+}, and CoA). † $P < .001$ with respect to controls (NAD, Ca^{2+}, CoA, and Triton). ‡ $P > .02$ with respect to controls (NAD, Ca^{2+}, CoA, and Triton). § $P < .001$ with respect to control (Ca^{2+} and CoA). ‖ $P < .005$ with respect to control (NAD, Ca^{2+}, and CoA).

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