Atomic Clouds as Distributed Sources for the

Io Plasma Torus

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Abstract

We consider the implications of several recent developments for the neutral particle environment of Jupiter. We report the first detection of very hot S^+ ions with gyrospeeds comparable to the corotations speed, a phenomenon which would result from a neutral sulfur cloud. Current evidence supports the hypothesis that extensive neutral clouds of oxygen and sulfur exist and are important sources of ions and energy for the Io torus.

Introduction

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 UV line emission studies from ground-based and Earth-orbiting observations (see current reviews by Pilcher and Strobel, 1981; Brown, Pilcher and Strobel, 1981). These studies document a rich phenomenology, but also provide insight into the physical processes sustaining the 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: the first is the source location for these heavy ions; and the second is the process supplying energy to the observed optical and UV emissions. These are the starting points for modelling 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 constitute the dominant sources of ions and energy. This note recounts the existing evidence and reports a new observation of a very hot plasma ion component, a phenomenon consistent with ionization of cloud atoms. We assess this material to encourage the emergence of a more coherent picture of Jupiter's charged and neutral particle environments.

After the detection of the sulfur nebula by the [SII] collisionally-excited optical emissions (Kupo, Mekler, and Eviatar, 1976), it was suggested (Brown, 1978a) that the energy could be supplied from the thermalization of extremely hot, newly-created ions. Extensive clouds of highly-visible alkali metal atoms were known to exist near Io (Brown, 1974; Trafton, 1975). Ionization of such atoms by photoionization, charge exchange or electron impact would produce hot ions gyrating with speed similar to the relative motion of the ballistic atoms and the corotating plasma (57 km s^{-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^+ (Munch, Trauger and Roesler, 1977) and a reported large plasma scale height (Kupo, Mekler, and Eviatar, 1976) were interpreted by Eviatar, Siscoe, and Mekler (1979) to indicate a large temperature anisotropy in plasma heavy ions. They suggested 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 an artifact of ion injection over the range of magnetic latitudes sampled by Io's orbit (Siscoe and Chen, 1977). Eviatar, Siscoe and Mekler (1979) argued for a low-density, low-mass plasma ($\approx$500 cm^{-3}) which would permit this temperature anisotropy by reducing the importance of collisions.

Each of these three underlying inferences has been found to be incorrect. We report below the detection of ions with gyrospeeds near the corotation speed. Parallel and perpendicular temperatures do vary with position in the plasma, but retain isotropy (reviewed by Pilcher and Strobel, 1981). The plasma is dense: charge densities in the range 2-5 x 10^3 cm^{-3} first reported from optical studies by Brown (1976, 1978b) have been generally confirmed by in situ measurements (Warwick et al., 1979; Bagenal et al., 1980). Collisions are important for the jovian plasma, and there is no remaining kinematical requirement for an ion source completely localized at Io.

The hot-ion power mechanism was raised again by the experimenters of the Voyager UV spectrometers (Broadfoot et al., 1979). Since sulfur and oxygen atoms would yield about 540 eV and 270 eV per ionization, respectively, the observed total emission rate of 2-3 x 10^{12} W (Shemansky, 1980a) implies a total ionization rate of about 4 x 10^{28} s^{-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 at the Voyager epoch, and the required production rate exceeded by three orders of magnitude the visible production rate of sodium ions from the parent atomic cloud (Smyth and McElroy, 1978; see also Brown, 1981b).

New evidence for hot ions resulting from the ionization of cloud atoms

It has been widely believed that apparent absence in spectral observations of a hot ion component indicates a lack of newly-created ions, and hence the relative unimportance of extensive atom clouds as an ion source. However, we wish to point out that there is an observational bias in favor of cool distributions in energy- or velocity-dispersive detections: the signal from a hot component is spread out relative to the concentrated response to a cool component. This is illustrated in Figure 1, a recently obtained spectrum of [SII] 6716A, 6731A at the eastern elongation of Io's orbit. The emission line is much broader than the instrumental line profile, consequently its shape is an approximate map of the distribution of ion velocities. A single Maxwellian distribution ($T \simeq 18$ eV) fits the line core, but not the wings, which are satisfactorily described by a 540 eV component containing one-third the total S^+ density.

The broadening of an observed spectral line is commonly described simply by a width, which is interpreted using a theory invoking some physical mechanism to predict a detailed lineshape, from which the width alone is extracted for comparison with observation. This procedure discards information if the observed and theoretical line profiles differ, and this is true in the current case. The jovian [SII] emission line is not well described by a single-temperature Doppler line profile. While nothing detailed can be said about the distribution of ion high speeds at this point, their existence is required by the spectrum in Figure 1.

This result is parallel both in form and implication to the suggestion by Bagenal and Sullivan (1981) that a very high-energy, pseudo-continuum with a high-speed cutoff may underly some of the Voyager PPS spectra; that is the expected signature of newly-created ions. The disappearance of this indication of new ions outside of 6 R_J may be once again due to lower detectability in the presence of that region's high plasma temperatures.

Existing evidence for major neutral atom clouds

Brown (1981a) succeeded in detecting an atomic oxygen cloud by faint emission at 6300A. The estimated oxygen density of 30 cm^{-3} implies an source $\sim 10^{28}$ s^{-1}. There is uncertainty about both the volume occupied by the neutral oxygen and its lifetime, and the supply rate estimate is proportional to their ratio. However, the atom partial torus grows in longitudinal extent proportionally with time (Smyth and McElroy, 1977). 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 those constituents which are observed in atomic clouds, but only under the assumption of a common cloud origin for all species. The Voyager plasma science experiment found 1-10% for Na and 17-25% for O (Bagenal and Sullivan, 1981), implying total sources $10^{28\pm.7}$ atoms s^{-1} (from Na) and of order 3 x 10^{28} atoms s^{-1} (from O). Thus, optical observations of the detected neutral species imply similar values of the total neutral production rate.

In situ measurements of the energetic charged particles in the Jovian magnetosphere have also provided interesting information on the neutral atomic clouds. For example, the probable detection of energetic neutral particles ejected from the Jovian system has been recently reported by Kirsch et al. (1981). The corresponding loss rate for the 14-31 keV particles is $<10^{25}$ s^{-1}. Following the suggestion by Cheng (1980), the authors suggested that these energetic neutrals were produced by charge exchange reactions between the inwardly diffusing charged particles and the atoms in the Io neutral clouds.

In a study of the pitch-angle distributions of ions detected by the LECP experiment on Voyager 1 spacecraft, Lanzerotti et al. (1981) have also found supporting evidence for the charge exchange process. The ion pitch-angle distributions for particles with energies 1.05-2.0 MeV are pancake-like outside the orbit of Io, but the pitch angle distribution measured at 5 R_J has a dumb-bell shape, with a significant reduction in the particles mirroring at low magnetic latitudes. As first pointed out by Cheng (1980), such a pitch-angle dependent effect in charged particle loss is expected from the charge exchange process. By a somewhat more detailed consideration of the radial diffusion and loss of the magnetospheric particles between 5 and 8 R_J, Ip (1981) has shown that the observations imply a number density of about 50 cm^{-3} for neutral oxygen and sulfur atoms in the vicinity of Io's orbit That estimate is consistent with the number density obtained by Brown (1981a) from optical observations.

Besides influence on 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 to substitute hot new ion with gyro-energy of a few hundred eV for the cold ions with a thermal energy of a few eV. This is particularly important for the region of the cold SII nebula inside of 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 the S and O atoms and ions given by Kunc and Judge (1981), the average lifetime against charge exchange loss for the S^+ and O^+ ions can be estimated to be about 4×10^5 sec 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 $\sim 10^{28}$ s^{-1}. The charge exchange ionization rate of the neutral atoms, of course, would be the same.

Discussion

These factors favoring the distributed neutral cloud do not rule out the Io ionosphere as a source for the torus plasma. There is, however, little evidence supporting the view that it is the dominant source. One estimate, which relates the field-aligned current flowing across Io to the pickup of ionospheric mass, yields an ion production rate of about 10^{28} ions s^{-1} (see Cloutier et al., 1978; Ip and Axford, 1980; Goertz, 1980). However, in a study of the Voyager UV data, Shemansky (1980b) has reported an upper limit production rate of 10^{27} ions s^{-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 are probably dominant in maintaining the Io torus.

Heating mechanisms other than the 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 the heavy ions and the global thermal structure of the torus (e.g. Ip, 1980). The relative importance of different heating and cooling effects (i.e. fast thermalization of the hot ions via collective plasma processes as proposed by Wu and Davidson (1972) and Hartle and Wu (1973) vs. energy transfer via ion-ion and electron-ion Coulomb collisions) must be evaluated in connection with the analysis of the observational data as outlined in Fig. 1.

Conclusion

Recent studies from spacecraft and ground-based observatories have provided a first-order description of that region's composition and physical state, also its spatial and secular variability. In this note we have combined various lines of observational evidence to illuminate the underlying physical processes delivering ions and energy to the jovian plasma. Extensive clouds of neutral sulfur and oxygen atoms could perform these functions, and their existence is either compatible with or apparently required by the observations.

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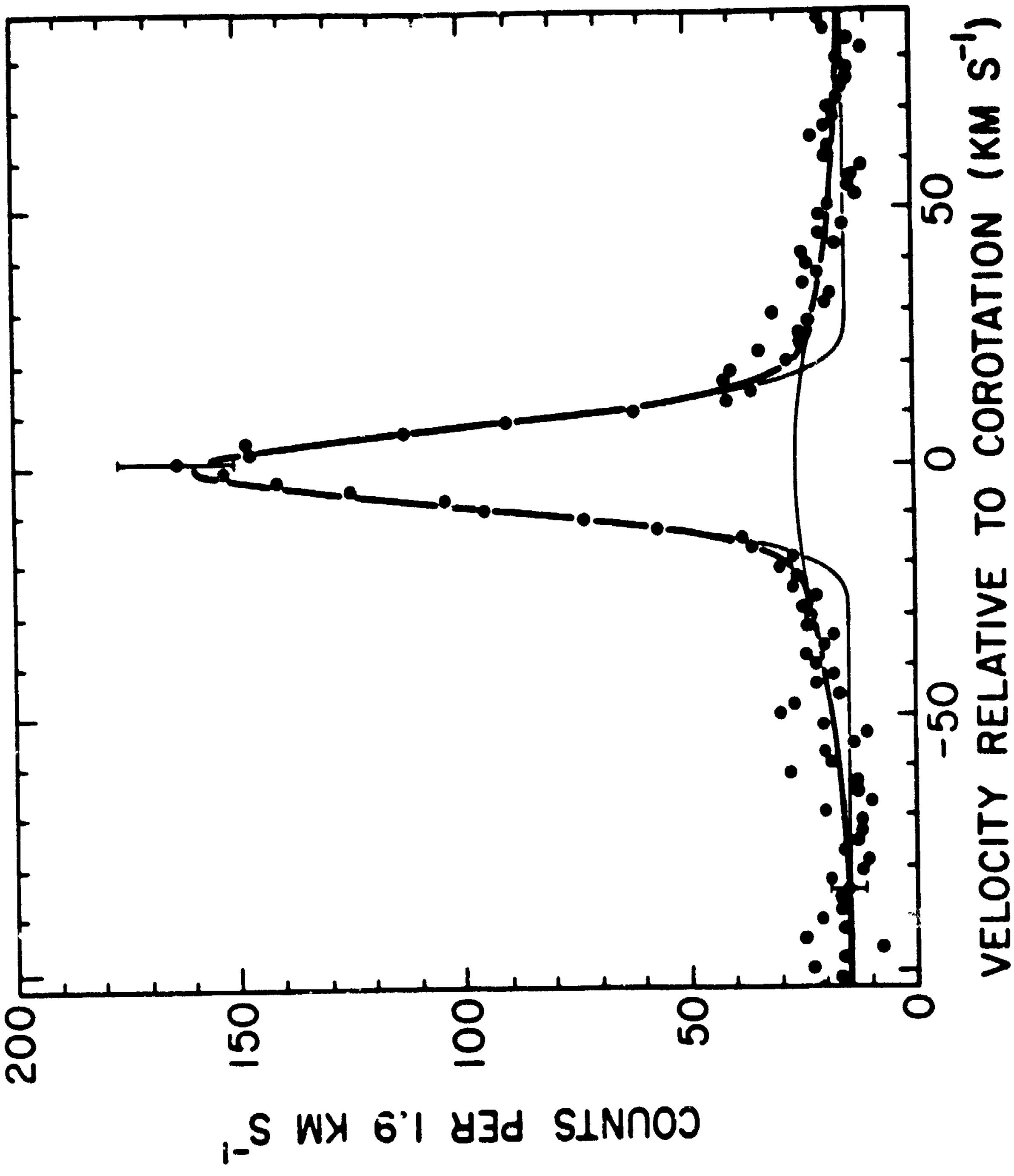
Figure Caption

Figure 1. A spectrum of [SII] emission from the Io torus. The dots are a combination of the recorded photons in 6716A and 6731A features: the two line centers have been overlapped and the responses summed. The Doppler relationship was used to produce the velocity scale from a detailed wavelength dispersion solution.

The faint curves shown Maxwellian velocity distributions having kinetic temperatures 18 eV and 543 eV, which fit the line core and wings, separately. The bold curve is a sum of those cold and hot components, weighted respectively by 71% and 29% of the total light.

The observation was made by R.A.B. on 1981 February 24, 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 .19A (6.2 eV) full-width at half-maximum. The detector, a Reticon array preceded by a cooled image intensifier (Davis and Latham, 1979), recorded individual photoelectron events. The effective slit width measured 7.2 x 1.1 arc-sec or .3 x .05 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.



200
150
100
50
0
COUNTS PER 1.9 KM S-1
-50
0
50
VELOCITY RELATIVE TO COROTATION (KM S-1)

Figure 1.