11

Io's neutral clouds, plasma torus, and magnetospheric interaction

Nicholas M. Schneider and Fran Bagenal

11.1 INTRODUCTION

The Jovian system would be dramatically different if Io were not volcanically active. The orbital resonances that power tidal heating not only alter Io beyond recognition, but also extend Io's influences throughout the Jovian magnetosphere, to other satellites, and even into its quadrant of the Solar System (Figure 11.1). In this chapter we will begin with a discussion about the material escaping from Io, and the vast neutral clouds it creates. We continue with the ionized ring of plasma called the Io torus that is created from Iogenic material. We then cover the way in which the plasma in turn affects Io and the other satellites, and conclude with the broader effects on the magnetosphere at large, the aurora at Jupiter, and the escape of material into interplanetary space.

The discovery of Io's broad influences on the Jovian system far predated the discovery of volcanism. Bigg (1964) discovered Io's controlling influence over Jupiter's decametric radio emissions. Brown (1974) observed sodium emission from Io, which Trafton (1974) soon demonstrated to come from extended neutral clouds and not Io itself. Soon thereafter, Kupo and Mekler (1976) detected emissions from sulfur ions, which Brown (1976) recognized as coming from a dense plasma analogous to an astrophysical nebula. With the prediction of volcanism by Peale *et al.* (1979) just before its discovery by *Voyager 1* (Morahito *et al.*, 1979), a consistent picture of Io's role began to emerge. *Voyager 1*'s discovery of Jupiter's aurora and extreme ultraviolet emission from the torus (Broadfoot *et al.*, 1979), along with its *in situ* measurements of the magnetosphere (reviewed in Dessler, 1983) extended our awareness of Io's effect on the larger system.

The ensuing 25 years of observation by interplanetary missions, Earth-orbiting observatories, and ground-based telescopes has deepened our understanding of Io's

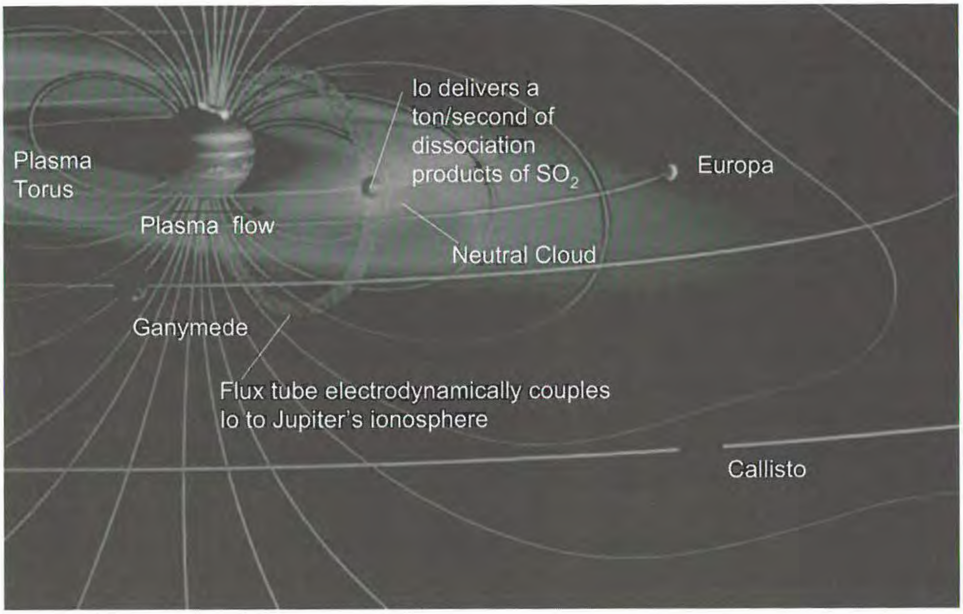

Figure 11.1. The main components of the Jupiter–Io system and their primary interactions. (See also color section.)

influences. Highlights include *Galileo*'s many close fly-bys of Io, with detailed fields-and-particle measurements of Io's interaction with the magnetosphere, and *Cassini*'s months-long ultraviolet observation of the torus (Steffl *et al.*, 2004a,b, 2006). Progress from Earth-based studies include the sensitive Hubble Space Telescope (HST) ultraviolet observations of Io's atmospheric emissions, and ground-based observations of new atomic and molecular species in Io's atmosphere and the plasma torus.

This chapter reviews the phenomena above with emphasis on their big picture connections to Io's volcanism. There are several excellent reviews on this same subject with greater technical detail. These topics are covered in several chapters of the book *Jupiter* (Bagenal *et al.*, 2004): Thomas *et al.* reviews the clouds and torus, Saur *et al.* and Kivelson *et al.* review magnetospheric interactions with Io and other satellites, and four additional chapters review the broader magnetospheric context. Our state of understanding before *Galileo* is summarized in Spencer and Schneider (1996).

11.2 NEUTRAL CLOUDS

Io's effect on the Jovian magnetosphere can be largely attributed to the fact that it has an unexpectedly large atmosphere for a small moon. Io's low gravity allows the atmosphere to escape by a variety of processes, and volcanic outgassing resupplies

Table 11.1. Material escaping from Io.

Material	Primary evidence	Proportion	
S, O	Atomic emissions in corona, neutral cloud Ionic emissions from torus Particle detection in torus	>90%	By element
Na, K	Atomic emissions from neutral clouds	1–few%	
Cl	Ionic emissions from torus	1–few%	
Molecules	Ion cyclotron waves near Io SO_2^+ or S_2^+ particle detections in cold torus NaX^+ in sodium stream	The proportion of mass escaping Io in molecular vs. atomic form is unknown	
Dust	Io-correlated dust streams composed primarily of NaCl	The proportion of mass lost in the form of dust is <0.1%	

it on a timescale of hours to days. The properties of the atmosphere, and the key processes responsible for maintaining it, are described in Chapter 10.

Io loses approximately 1 ton per second to the neutral clouds and magnetosphere, primarily atoms and molecules of sulfur and oxygen (Table 11.1). Over the age of the solar system, this accumulates to a net decrease in radius of about 2 km. While this loss is significant, Io is not in danger of running out of SO_2 in the lifetime of the solar system. It is plausible, however, that other volatile species such as H_2O were originally present on Io but then were completely lost earlier in its history through processes now depleting Io of SO_2 (Spencer and Schneider, 1996).

Escaping material is composed of the elements of volcanic volatiles SO_2, S_2, NaCl, KCl, and other plausible combinations. The dust detected far from Io has recently been shown to be primarily salt – NaCl (Postberg *et al.*, 2006), but supplied at too low a rate to account for all the sodium and chlorine in the system. It is noteworthy that although silicate volcanism occurs on Io's surface, no refractory elements such as Si, Fe, Mg, or Al have been detected in the neutral clouds or torus. Upper limits on these species place them below 1% in overall composition and well below their cosmic abundances relative to other observed species (Na *et al.*, 1998). This supports the prevailing theory that escape from Io occurs through the intermediary of the atmosphere, with little or no direct ejection from the surface. Note that direct ejection by the volcanoes is also considered negligible, as vent velocities even up to $1\ \mathrm{km\,s^{-1}}$ are small compared with Io's escape velocity of $2.6\ \mathrm{km\,s^{-1}}$.

Escape from Io occurs in a complex region where magnetospheric plasma flows through Io's upper atmosphere (Figure 11.2). The plasma in the torus approximately corotates with Jupiter, meaning that it travels at about $74\ \mathrm{km\,s^{-1}}$ at Io's orbit, overtaking Io which orbits at $17\ \mathrm{km\,s^{-1}}$. Torus plasma is partially diverted around Io by a conducting ionosphere, but ions and electrons flow through Io's exosphere at speeds of $57\pm30\ \mathrm{km\,s^{-1}}$ (discussed further in Section 11.4) and undergo a variety of collisional interactions. In the interaction region, plasma physics, atmospheric

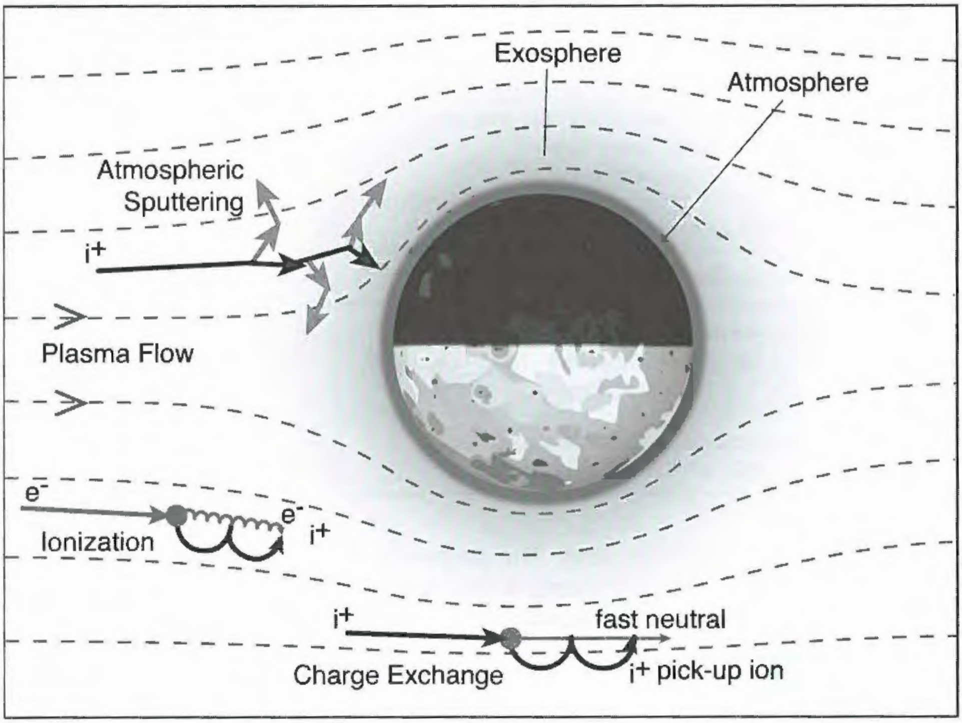

Figure 11.2. Important plasma/atmosphere interactions near Io. For simplicity the diagram shows the gyromotion for pick-up ions and electrons, but not for incident ions or electrons. The scale of the gyromotions has been greatly exaggerated: the gyroradius of a pick-up oxygen ion is 5 km, much less than Io's radius, and that of an electron is about 40,000 times smaller than the ion's. (See also color section.)

physics, ionospheric physics, atomic physics, and molecular physics all play controlling roles, which may explain why no comprehensive model of this region yet exists.

The variety of ion/electron/atom interactions each has key effects for the magnetosphere. Most importantly, torus ions collide with neutral atoms in the atmosphere, which in turn collide with other atoms in the process known as sputtering. Typically, one torus ion can transfer enough momentum for several atmospheric atoms or molecules to be ejected into Io's corona or possibly to escape from Io altogether. This is the primary pathway for material to be supplied to the neutral clouds and ultimately to the plasma torus. A second key reaction is electron impact ionization, in which a torus electron ionizes an atmospheric atom, which is then accelerated up to the speed of the plasma and leaves Io. Torus ions can also charge exchange with atmospheric neutrals, which results in a fresh ion and a high-speed neutral. Elastic collisions between ions and atoms can also eject material at speeds between those resulting from sputtering and charge exchange. Finally, electron-impact dissociation breaks down molecules into their component atoms. Approximate lifetimes for

Table 11.2. Characteristic timescales for escaping materials. These approximate timescales apply in the torus, outside of the interaction region (n = 2,000 electrons cm^{-3}, T_e = 5 eV).

Process	Example	Lifetime
Electron impact ionization	$O + e^- \rightarrow O^+$ $S + e^- \rightarrow S^+$ $Na + e^- \rightarrow Na^+$	~100 hr† ~ 10 hr ~ 4 hr
Charge exchange	$O + O^+ \rightarrow O^+ + O^*$	~ 50 hr
Electron impact dissociation	$SO_2 + e^- \rightarrow SO + O$	~ 4 hr
Transport time to Hill sphere (6 R_{Io}) Transport time across cloud (6 R_J)	3 km s^{-1} (average) 3 km s^{-1} (initial)	~ 1 hr ~ 20 hr

† Hot electrons may shorten the ionization lifetime for O (and other ions with high ionization potential) by a factor of 10.

examples of these processes are listed in Table 11.2. The tabulated numbers apply to average conditions in the torus, as conditions in the interaction regions are not well known. The tabulated values are therefore of greatest use for relative comparisons to other numbers in the table, as opposed to their numerical values.

Material escaping from Io forms distinct features depending primarily on the speed and direction characteristics of the ejection process (Figure 11.3). Sputtering, for example, produces a broad angular distribution of particles in a velocity distribution weighted toward low velocities. Most sputtering products have much less than Io's 2.6 km s^{-1} escape velocity, and therefore travel along ballistic trajectories which will return them to Io (barring other reactions). These particles populate the corona or exosphere, which extends from Io's exobase to the boundary of the Hill sphere at about 6 R_{Io} where Jupiter's gravity begins to dominate.

The sputtering velocity distribution has a tail extending above the escape velocity, and these atoms will form neutral clouds extending many R_J away from Io. The morphology of the clouds is controlled by celestial mechanics (dominated by Jupiter's gravity) and by loss processes from interactions with the plasma torus. An initially spherical cloud of atoms escaping radially from Io takes on a very different shape as Jupiter's gravity takes over. Atoms ejected backward at a few km s^{-1} relative to Io's orbital motion of 17 km s^{-1} have a speed below that needed for circular motion around Jupiter. These atoms will fall inward toward Jupiter, converting potential to kinetic energy and end up getting ahead of Io in its orbit. Similarly, particles whose launch velocities are aligned in the direction of Io's orbital motion have higher than circular velocities, and will travel on ellipses that take them farther from Jupiter, where they slow down and fall behind Io. The net result purely from celestial mechanics is a neutral cloud with one part extending ahead and inside Io's orbit, and another extending outside and behind. In about 20 hr, atoms launched from Io at only a few km s^{-1} can reach distances of 6 R_J ahead of, or behind, Io.

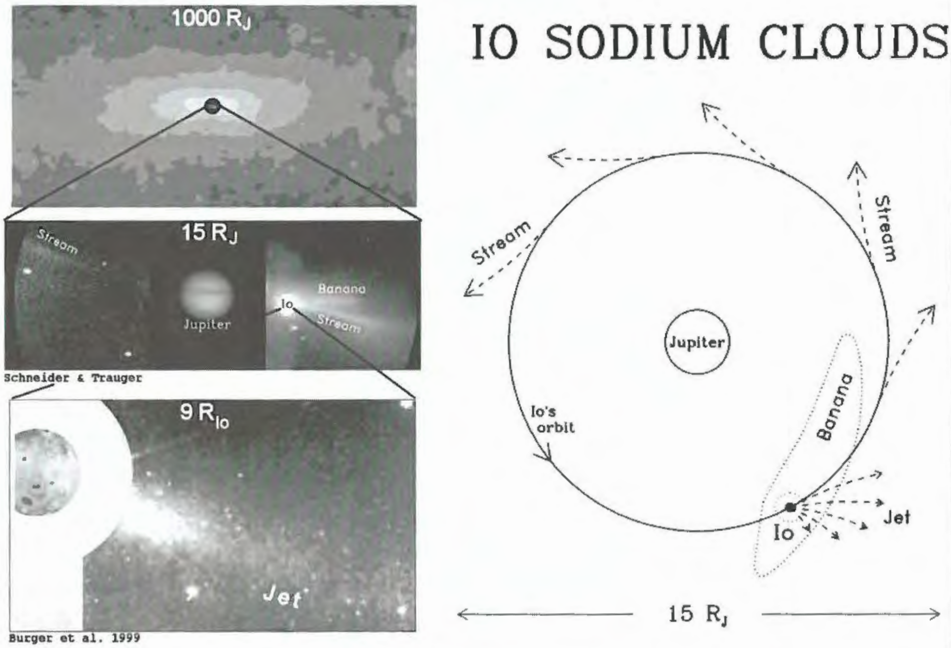

Figure 11.3. (*left*) Io's sodium cloud on three spatial scales, as imaged by ground-based observations of sodium D-line emission. (*right*) The features observed on the left are explained by the three atmospheric escape processes shown schematically. The "banana" cloud and stream are explained further in the text. (Courtesy Jody Wilson.)

The basic cloud shape resulting from celestial mechanics is further sculpted by loss processes arising from the plasma environment (Figure 11.3). Note that the leading cloud lies inside Io's orbit where the plasma is cool, so atomic lifetimes are significantly longer than those listed in Table 11.2. The "trailing cloud" is subjected to plasma warm enough to ionize much of the cloud, though the ionization rate depends on the species involved. Electrons with average energies $\sim$5 eV include enough in a high-energy tail to strip electrons from atoms with ionization potentials of 4–20 eV. (A small population of even hotter electrons may play an even more important role in ionization.) At one extreme, the 4-hr sodium lifetime against ionization is short compared with a typical transport time of 20 hr, so the trailing cloud is virtually non-existent. The decimation of the trailing cloud is so complete that at one point it was concluded that no atoms were ejected in that direction (i.e., from Io's leading hemisphere). Now, the accepted explanation for the sodium "banana" cloud that leads Io in its orbit is the rapid ionization of sodium atoms in the trailing cloud.

Other ejection processes create the distinct features in Io's neutral clouds shown in Figure 11.3. In a charge exchange reaction between torus ions and atoms in the neutral cloud, the ion takes an electron from the atom, becoming neutral and therefore decoupled from the magnetic field. The fast neutral escapes the Jovian system, since it retains its velocity as an ion: the $\sim$70 km s^{-1} bulk velocity of the plasma plus a smaller random component from its thermal energy. (The escape velocity from Jupiter at the distance of Io's orbit is only $24\,\mathrm{km\,s^{-1}}$.) A second process known as molecular ion dissociation also creates a fast neutral spray. In one known example, sodium-bearing molecular ions (NaX^+, possibly $NaCl^+$) are picked up in the torus and carried downstream. Since dissociation of molecular ions is as fast as dissociation of neutral molecules, the ion is broken apart, creating a fast sodium atom some of the time. The trail of fresh molecular ions downstream from Io leads to a "stream" of fast neutrals that almost encircles Jupiter. Over many Io orbits and Jupiter rotations, fast neutrals create a tutu-shaped spray of sodium atoms with escape velocity from Jupiter. These populate the vast region sometimes called the Mendillosphere (Figure 11.3, top) after its discoverer (Mendillo *et al.*, 1990).

Clouds of sulfur and oxygen are much denser than the sodium cloud, but are governed by similar dynamics. Differences in reaction rates lead to dramatic differences in their spatial distributions. For example, the longer ionization lifetime for O and S (see Table 11.2) means that the outer trailing cloud may be comparable in density and extent to the inner leading cloud, an important fact when locating the source of fresh plasma. The molecular ion stream may be unique to sodium-bearing ions since their low ionization potential favors their creation in Io's ionosphere, meaning that "streams" of fast oxygen or sulfur are not expected. But the shorter lifetime of O^+ against charge exchange leads to a larger proportion of fast neutral oxygen atoms created through this process, and a correspondingly smaller proportion of oxygen relative to sulfur in the torus than the 2 : 1 ratio expected from the break-up of SO_2.

Our understanding of the sodium clouds is much better than that of oxygen and sulfur clouds, even though sodium is only a trace species. This puzzle can be traced to sodium's atomic structure, which allows sodium to scatter sunlight efficiently at visible wavelengths. Oxygen and sulfur atoms scatter sunlight at only ultraviolet wavelengths, where the Sun produces little light and where observations can only be made from space. These species therefore radiate by electron impact excitation which produces much fainter emissions.

11.3 THE PLASMA TORUS

The loss of neutral cloud atoms through ionization is the primary source of material for the plasma torus. Thus, the torus is a self-sustaining plasma, since it is the impact of torus ions on Io's surface or atmosphere that causes the sputtering that supplies the clouds in the first place. The stability of this feedback loop may depend on the nature of the plasma/atmosphere interaction described in the next section. Figure 11.4 shows the basic structure of the torus and its relationship to the neutral clouds.

Electron impact ionization of a slowly moving atom creates a fresh ion with a high velocity relative to the corotating plasma. Each pickup ion is therefore "picked up" by the fields that cause corotation, and spirals around its field line with a velocity equal to its initial motion "backward" relative to the plasma. Each fresh ion starts with a gyration velocity equal to the plasma flow speed in its rest frame, so has a gyroenergy

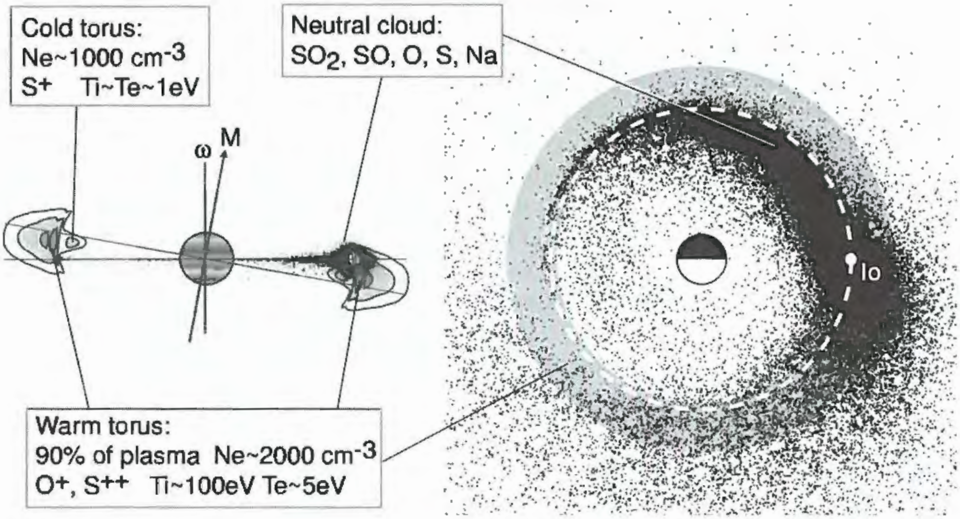

Figure 11.4. Schematic of the Io plasma torus and neutral clouds as seen from the side (*left*) and from above (*right*). Note that the plasma torus is tipped 7° relative to Jupiter's equator in a coordinate system that corotates with Jupiter, while the neutral clouds lie in the equatorial plane and move with Io along its orbit. In the side view, the torus is shown in cross section since the structure is basically the same throughout. The neutral cloud, however, is shown as a projection since its structure depends on Io's position.

dependent on its mass: 270 eV for O^+ and 540 eV for S^+ at Io's orbital distance. The energy of these fresh ions ultimately comes from Jupiter's rotation. The 57 km s^{-1} gyromotion of fresh pickup ions lies in the plane perpendicular to the local magnetic field. (If the gyroenergy were distributed into an isotropic Maxwellian distribution, the O^+ and S^+ ions would have temperatures of 2/3 their initial pickup energy (i.e., 170 eV and 340 eV, respectively).) Fresh oxygen pickup ions gyrate around magnetic field lines about twice per second with a 5-km gyroradius, as electrodynamical coupling to Jupiter's ionosphere causes the torus plasma to corotate with the planet (Figure 11.5).

The continuous ionization of the vast neutral clouds creates a ring of plasma encircling Jupiter near Io's orbit and moving around Jupiter at roughly the corotation speed. Some ions are created in Io's immediate vicinity, and others are picked up from the vast neutrals clouds many Io radii (or even Jupiter radii) away. Ions appear to reside in the torus for the order of 100 rotations, meaning that each rotation of the torus through the neutral clouds adds only $\sim$1% new plasma. Coincidentally, the approximate ratio of neutral lifetime ($<$20 hr) and plasma transport timescale ($\sim$40 days) is also about 1%.

The study of the torus requires understanding of both microscopic and macroscopic behavior, much as geology combines understanding both rheology and landforms. First we will discuss the small-scale behavior of the plasma, and then return to the large-scale view.

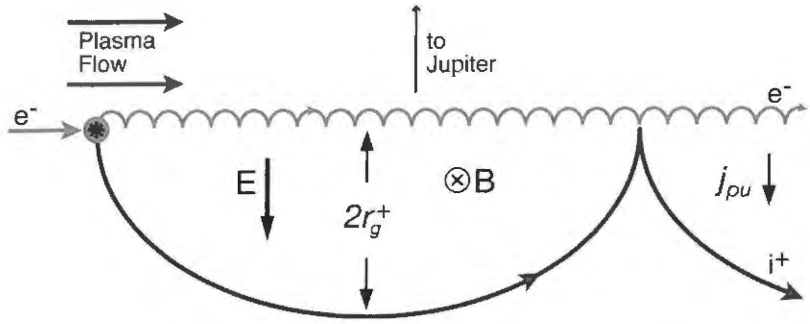

Figure 11.5. The pickup process. Pickup ions and electrons travel on cycloids in the frame co-moving with Io, resulting from the addition of 57 km s^{-1} bulk velocity and 57 km s^{-1} gyrovelocity. The ion and electron cycloids are offset in opposite directions because of their opposite charges. Note that the electron cycloid is greatly enlarged for visibility.

One valuable microscopic view studies a representative torus "cubic centimeter" in isolation, supplied with neutral atoms. Detailed models (described as "Neutral Cloud Theory") consider reactions between ions and electrons, including those responsible for ionization and ion chemistry, for energy flows between species, and for radiation at all wavelengths. Models also assume plasma leaves the torus volume by outward radial transport, with characteristic lifetimes of tens of days. The goal is to explain the basic observed conditions of the torus, with a density of about 2,000 electrons cm^{-3}, an ion temperature of ~100 eV, an electron temperature of ~5 eV, and a composition dominated by O^+, S^{++}, S^+, O^{++}, and S^{+++} ions.

The first component of such models is mass balance. Only about one-third of the neutrals escaping from Io add net mass to the torus through electron impact ionization. Two-thirds of the neutrals undergo charge-exchange collisions in which the neutral becomes a fresh ion, and the incident torus ion becomes an escaping fast neutral. Thus, charge exchange can add energy to the torus without adding mass. The relative importance of ionization and charge exchange may fluctuate. Models of periods of high neutral source (e.g., at the time of the *Voyager 2* fly-by) are consistent with the transport rate increasing with source strength and charge exchange becoming less important.

The second component of such models is energy balance, which is more complicated (Figure 11.6). Early attempts of modeling the torus plasma assumed the creation and acceleration of fresh ions to be the sole source of energy in the torus. The fresh ions lose thermal energy to the ambient ions though Coulomb collisions, and the ambient ions similarly lose energy to ambient electrons. Ultimately, the torus electrons lose energy by moving electrons bound to ions into excited states, leading to the prodigious extreme ultraviolet (EUV), ultraviolet, and visible emissions from the torus. Thus, energy cascades from the warmest to coolest populations (see Figure 11.6).

Radiation is a rapid drain on the energy of torus electrons: each emitted EUV photon saps 10–20 eV from an electron, and the total energy contained in the ~5 eV

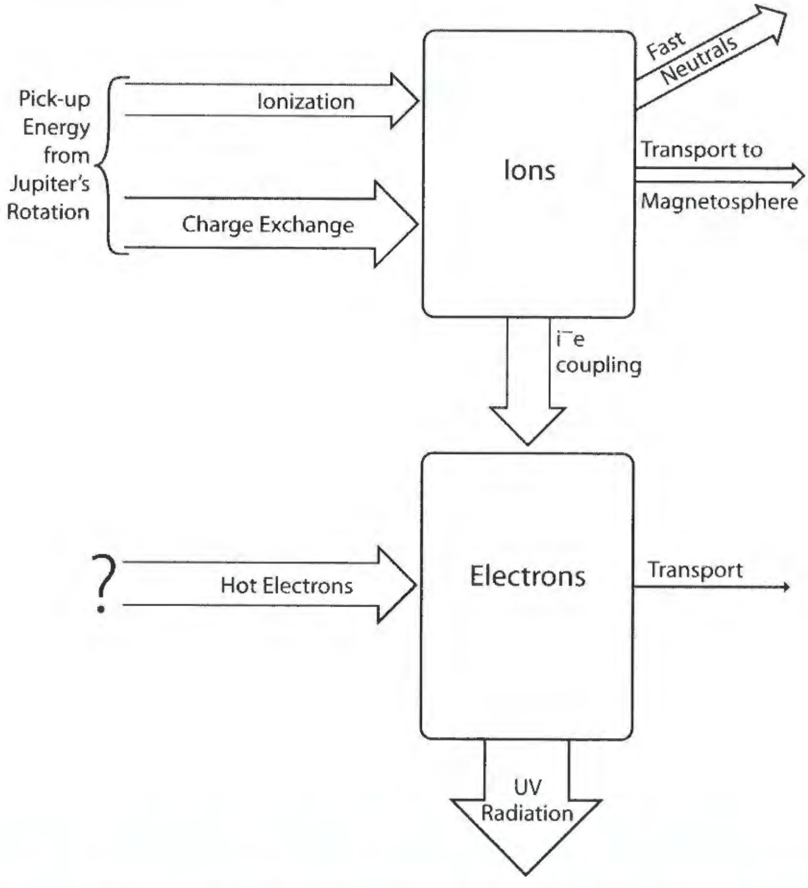

Figure 11.6. Typical energy flows in the Io plasma torus. The width of the arrows show the approximate fraction of energy on a particular path. Note that most or all of the energy ultimately is tapped from Jupiter's rotation, and most leaves through ultraviolet radiation caused by electron impact excitation of the ions.

thermal component of the electron distribution could only power the emissions for ~9 hours if the electrons were not rapidly re-energized. Similarly, each ionization takes at least 10 eV (and up to 35 eV for higher ionization states) from an electron, highlighting the importance of electrons at super-thermal energies.

Detailed modeling has shown that the supply of energy from fresh ions alone is not enough to maintain electrons hot enough to both power the observed radiation and maintain the ionization state. Simply increasing the ionization rate cannot solve this "energy crisis", since this also increases the energy drain to radiation and ionization. Thus, it is actually an "energy per ion" crisis, with too little energy being brought in by pickup to fuel each ion over its lifetime in the torus. Extra energy sources are required, with super-thermal electrons as the leading candidate, since they enhance ionization (particularly to higher ionization states) and increase the

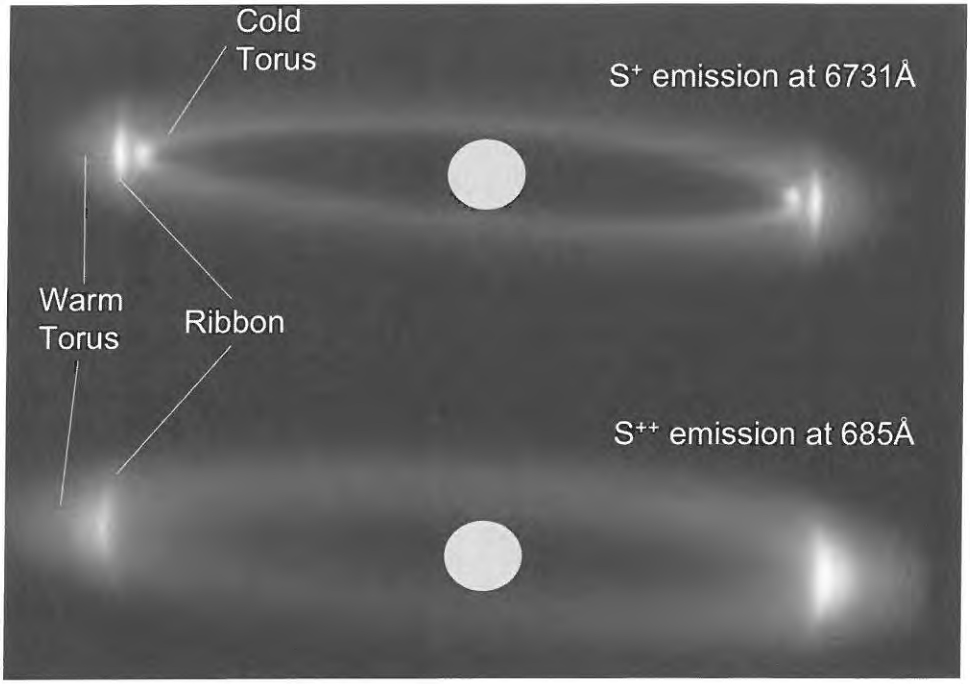

Figure 11.7. Regions of the plasma torus. This computed image shows optical S^+ emission (*top*) and EUV S^{++} emission (*bottom*). Note that S^+ dominates the cold torus and S^{++} dominates the warm torus. The ribbon is a tall, narrow ring which appears bright at the edges of the torus because of projection effects. The ribbon is typically the most prominent of the three regions for S^+, while in S^{++} emission the ribbon is a slight brightening at the inner edge of the warm torus. The structure of the torus can exhibit strong longitudinal variations, and the relative brightnesses of different regions can vary with time.

EUV output. Populations of only a few per cent of electrons that are $\sim 10\times$ hotter than the ambient electrons can close the gaps (in both ionization state and EUV emission rate) between models and observations. The specific source of energetic electrons is not yet identified, though there are several plausible theories. The remaining flow of energy comes from pickup ions, through ion–electron coupling to ultraviolet radiation. The contribution of hot electrons seems to vary substantially from $\sim 11\%$ during times of high source/transport rate (*Voyager 2*) to $\sim 60\%$ at times of low source/transport rate (*Cassini* fly-by, January 2001). Ultimately, very little of the energy created in the torus is transported into the magnetosphere beyond the torus, since much of the energy is lost by radiation and the escape of fast neutrals through charge exchange.

A macroscopic view of the torus provides a wealth of information that complements the energy insights derived from the preceding microscopic view. The structure of the torus reveals the magnetic and electric fields that shape it, and the transport of mass and energy through the system.

The basic shape of a tilted ring of plasma results from Jupiter's tilted magnetic field and its rapid 10-hr rotation (Figure 11.7). Torus plasma in Jupiter's magnetic field is confined toward the equator not by magnetic mirroring but by centrifugal forces. Jupiter's rapid rotation means that a corotating ion at Io's orbit experiences about 1 g of force outward from the rotation axis. Individual ions spiral around field lines several times per second while oscillating up and down along field lines every few hours, all while corotating with the planet. Ions in a Maxwellian velocity distribution will distribute themselves along the magnetic field line in a Gaussian centered around the point farthest from Jupiter's rotation axis. The locus of all such positions around Jupiter is called the centrifugal equator. In an approximately dipolar magnetic field tipped like Jupiter's, $\sim 10°$ from the rotation axis, the centrifugal equator has 2/3 of the tilt, or $\sim 7°$ from Jupiter's rotational equator. As the tilted torus corotates with Jupiter, the torus viewed from Earth appears to wobble $\pm 7°$. Non-dipolar components to the field can measurably warp the centrifugal equator.

The preceding particle perspective of the plasma is complemented by a fluid perspective. Even though the particles interact on timescales of hours to days, it is sufficient to view the plasma distribution along the field as a balance between the internal pressure of the plasma and the centrifugal force, much as an atmosphere lies in a balance between pressure and gravity. The fluid approach allows addition of further complexity associated with multiple species of differing mass and/or charge, thermal anisotropy, and the small electric field arising from any charge separation between ions and electrons.

The torus vertical structure reveals ion temperatures. The north–south ("vertical" = z-axis) variation in plasma density n about the centrifugal equator is a Gaussian function ($n = n_o \exp(-(z/H)^2)$) where the scale height H is primarily governed by the ion temperature T_i and the mass of the ions. For H in units of Jovian radii, R_J, we have $H \sim 0.64\,(T_i/A_i)^{1/2}$ where T_i is in eV and A_i is average ion mass in atomic mass units.

The torus radial structure reveals plasma transport processes. Though the strong magnetic field of Jupiter confines the torus plasma and inhibits radial spreading, the sulfur- and oxygen-dominated plasma filling Jupiter's magnetosphere must have come from Io. Therefore, transport across field lines must occur. Though the processes are not well understood, radial transport can be thought of as a diffusive process that is strongly influenced by centrifugal forces. Thus, outward flow is energetically favored, and inward transport is considerably slower (Thomas *et al.*, 2004).

We can now understand the three main regions of the Io torus. The outer ($\sim$6–7 R_J) region has hot ($\sim$100 eV), relatively fresh plasma that moves outward on timescales of tens of days. The narrow ($\sim$5.6–6 R_J) ribbon is a stagnated region of modest neutral sources and slow transport rates, so the plasma has time to radiate away thermal energy and cool to ion temperatures of $\sim$20 eV. The inner cold torus lacks a significant source of new ions, and transport is so slow that the plasma has time to cool to $<$1 eV.

The picture so far of a tilted ring locked to Jupiter's magnetic field and corotating with the planet is an excellent first approximation to the torus. The addition of several small but significant effects completes the picture. First, though the tilted ring is locked to the magnetic field, the plasma that makes up the ring is slowly slipping backward relative to the reference frame corotating with Jupiter. This sub-corotation is caused by imperfect coupling between the torus plasma and Jupiter's ionosphere (described in Section 11.5) and can result in plasma slipping 1–5% behind rigid corotation.

Second, plasma flow down Jupiter's magnetotail appears to impose an electric field across the torus, though the exact mechanism is not clear. As plasma travels around Jupiter, the electric field causes it to move a few per cent closer to Jupiter on the dusk side, and farther on the dawn side. This small shift causes non-linear compression and heating on the dusk side, making it up to twice as bright as the dawn side at EUV wavelengths.

Finally, longitudinal asymmetries in the torus create differences in brightness and/or composition from one side of the torus to the other. As Jupiter rotates, an observer monitoring either side of the torus will record periodic variations (see review by Thomas, 1993). Substantial progress in understanding these periodicities was made possible by months of torus monitoring by the *Cassini* UltraViolet Imaging Spectrometer (UVIS) during its Jupiter fly-by. Underlying asymmetries in electron temperature appear to cause asymmetries in ionization state and brightness. It has been suggested that there are two populations of hot electrons whose densities are modulated with magnetic longitude. One population corotates with the planet and the other sub-corotates. The torus exhibits significant asymmetries when the two modulations are in phase (Figure 11.8, top), and becomes longitudinally uniform when they are out of phase. The source mechanism of the hot electrons is unknown.

In addition to the "geometric" variabilities described above, the torus and neutral clouds undergo large temporal variability on timescales of months. On the face of it, such variation is not surprising, given the tremendous variability in volcanic activity and the volcanic origin of magnetospheric materials. But a deeper look shows the connection is not so obvious: volcanoes do not directly eject material into the clouds and torus, and Io's atmosphere is likely to play a buffering role on escape processes. The challenge in answering this central question has been collecting sufficient data on multiple phenomena thought to be causally connected.

To date no studies have unambiguously tied torus variation to volcanic activity, but several studies have connected a few links in the chain. Brown and Bouchez (1997), in a 6-month simultaneous study of the sodium cloud and sulfur torus, found that a rise in neutral sodium was followed several weeks later by an increase in sulfur ions. In a separate multi-year study, Mendillo *et al.* (2004) found a positive correlation between volcanic infrared brightness and the brightness of the distant sodium cloud (Figure 11.9). While these connections are promising, it bears noting that they both depend on sodium as a proxy for all neutrals – which is especially doubtful for the fast sodium supplying the distant sodium cloud. At present it is not feasible to monitor other neutral species as easily as sodium despite their expected higher densities.

The *Cassini* fly-by of Jupiter provided an excellent opportunity for observing many related phenomena in the torus. Figure 11.8 (top) shows the 30% decline in power of EUV emissions (normalized by 1/distance^2) observed as the spacecraft approached Jupiter. Properties of the plasma, derived by modeling the EUV

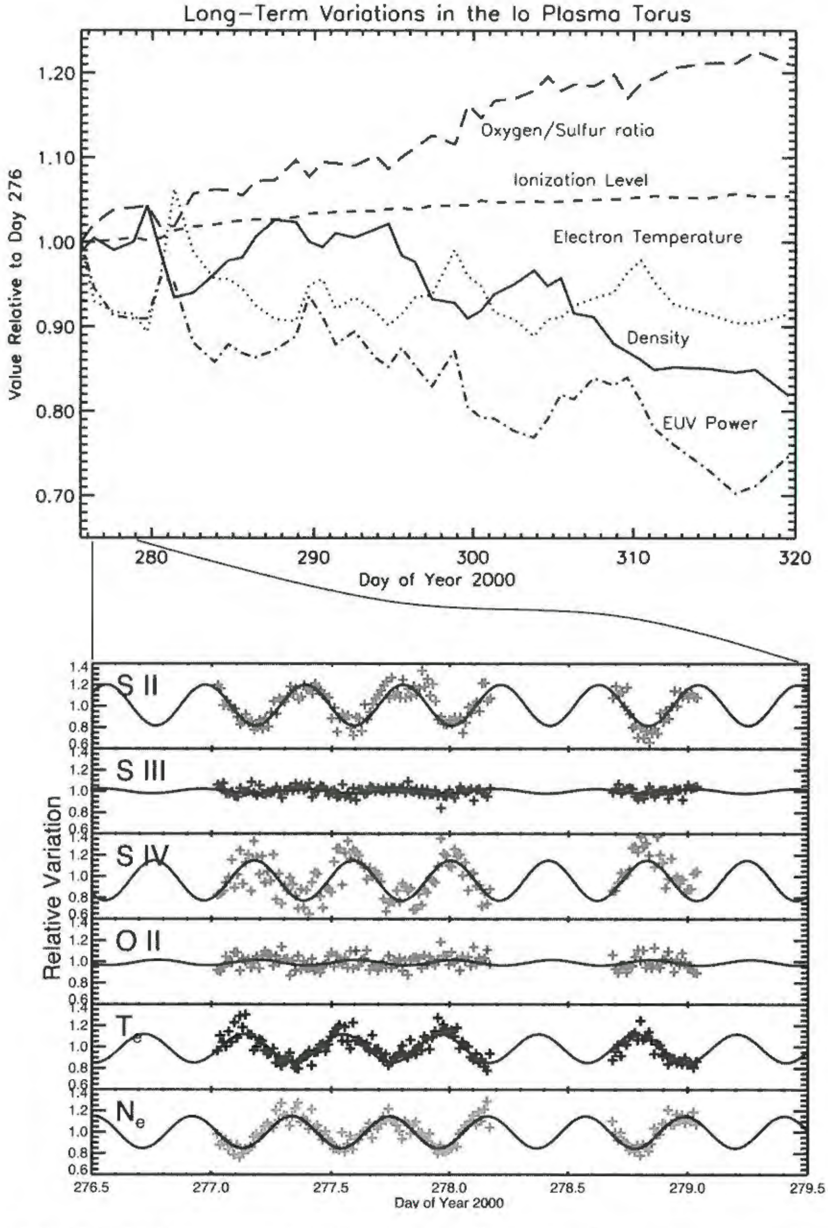

Figure 11.8. *Cassini* UVIS results for the short-term (*bottom*) and long-term (*top*) variation of the torus. Note that over periods of days, regular brightness variations are indications of structures in the torus moving in and out of the field of view. Over periods of weeks to months, variability is probably due to changing volcanic activity on Io. The inset shows a period of high periodic variation which waned in the following weeks but later reappeared at the same phase. The changing amplitude leads to the interpretation of two variations at slightly different periods which add when in phase but cancel when out of phase.

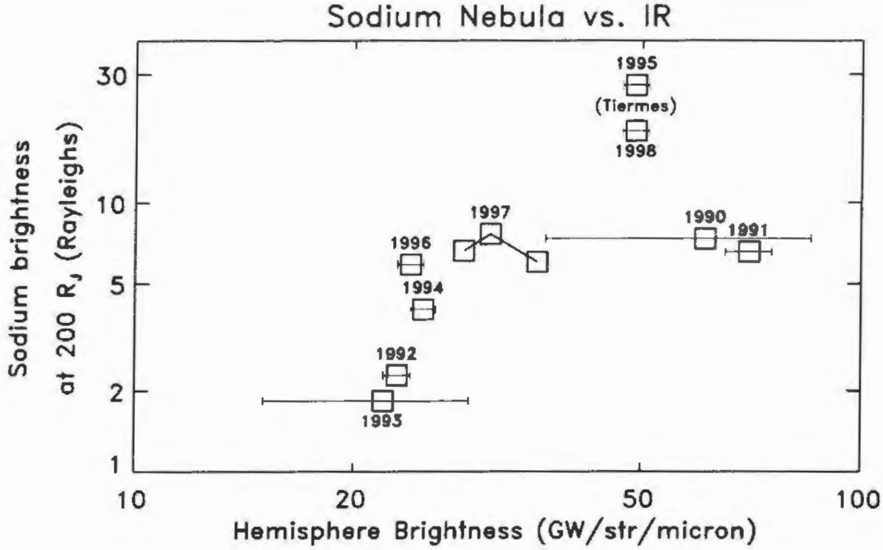

Figure 11.9. Tentative correlation between infrared emission from Io volcanoes (horizontal axis) and the distant sodium D-line emission (vertical axis). No specific mechanism connecting the two observables has been proposed (from Mendillo *et al.*, 2004).

spectra, showed corresponding long-term variations. These long-term variations are consistent with a ~3-fold increase in production of neutral atoms by Io over a ~1-month timescale occurring a month or so before UVIS started making observations of the torus (Delamere *et al.*, 2003). Such an increase in production of neutrals may have accompanied the ~1,000-fold increase in Iogenic dust coincident with *Galileo* observations of extensive surface changes and infrared emissions at the location of the Tvashtar Volcano (summarized in Krueger *et al.*, 2003). Variations in density and temperature of the warm torus (by factors of ~2) observed between *Voyagers 1* and *2*, multiple *Galileo* fly-bys, and *Cassini*, as well as comparable variations in ground-based observations of S^+ emissions, hint that torus conditions vary with Io's volcanic activity, though the specific process remains undetermined.

11.4 LOCAL INTERACTION WITH IO'S ATMOSPHERE AND NEUTRAL CLOUDS

The interaction of magnetospheric plasma with Io's atmosphere involves a complicated combination of electrodynamics, plasma physics, atmospheric processes, and atomic reactions. One of the first things to notice about the plasma flow around Io is that it is unlike the simple case of a rock submerged in a stream, where the fluid flows around and over the obstacle. Figure 11.10 shows that the strong magnetic field of Jupiter affects the interaction so that the flow around Io instead resembles fluid flow around a cylinder. (Note that a strong intrinsic magnetic field at Io has been ruled out

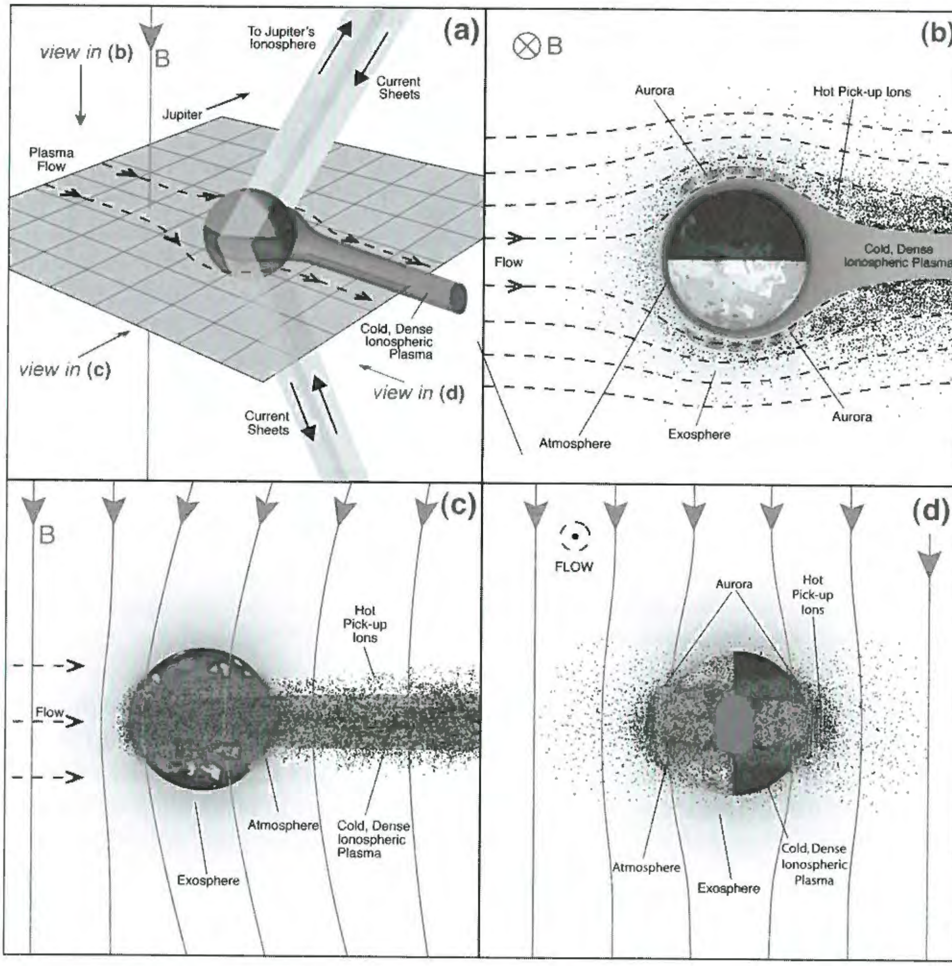

Figure 11.10. Four views of the interaction between Io and the plasma torus. (a) A 3-D view showing the current sheets that couple Io and the surrounding plasma to Jupiter's ionosphere. (b) A cross section of the interaction looking down on the north pole of Io, in the plane of Io's equator, when Io is located between the Sun and Jupiter (orbital phase 180°, local noon in magnetospheric coordinates). (c) A projected view of the Io interaction from the Sun toward Jupiter. (d) A projected view of the interaction from downstream in the flowing plasma (ahead of Io in its orbit). (See also color section.)

by *Galileo* fly-bys over the poles.) This simplified sketch of the interaction is based on telescopic observations of atmospheric properties and auroral emissions, multiple fly-bys by the *Galileo* spacecraft, and various different approaches to modeling pieces of the interaction puzzle.

Io's motion through the plasma creates a tremendous electrical current. A common physics lab experiment involves dragging a wire through a magnetic field and measuring the current that is induced along the wire. Basically, Io acts like a length of wire moving relative to the corotating plasma, which is threaded by Jupiter's magnetic field. The flanks of Io facing toward and away from Jupiter act as the ends of the wire. While Io's surface or interior may be modestly conducting, the current is more likely carried in other conducting materials surrounding Io, such as its ionosphere and the plasma produced by ionization of its neutral corona. Currents in a plasma do not easily flow across the magnetic field but do flow readily along the field, so the currents induced across Io are closed by currents that flow along field lines between Io and Jupiter's polar ionosphere in both hemispheres. Observations by the *Voyager 1* and *Galileo* spacecraft indicate that the net current in each circuit is about 3 million Amps.

This simple current system deflects most of the corotating plasma as it approaches Io. Most of the plasma flows around the moon with only $\sim$10% impinging on Io's deep atmosphere. The energy of the impact helps to heat and expand the atmosphere below, contributing to escape of neutrals. On the inner and outer flanks of Io, the plasma speeds up to get around the obstacle, though deeper in the atmosphere the flow may be slowed. The flanks are the main regions where the flowing plasma collides with the neutral atmosphere and corona: inelastic collisions heat the neutrals, electrons excite or ionize the neutrals, and ions and neutrals exchange electrons. Collisions between the plasma and neutrals allow the plasma to conduct some of the current across Io – a conduction current.

A little farther from Io, electron impact ionization of the neutral corona produces pickup ions which gyrate around the local magnetic field with a speed equal to the relative motion between the original neutral and the local plasma flow (see Figure 11.5). Ions have gyroradii of many kilometers, while the tiny mass of the fresh electrons results in very small gyromotion in the opposite direction. The difference in gyroradii of the fresh electrons and heavy pickup ions results in a small charge separation that creates a current in the radial direction – a pickup current. The relative contributions from the conduction current through Io's ionosphere vs. the pickup current generated by ion pickup remains an issue of debate that awaits more sophisticated models (e.g., see review by Saur *et al.*, 2004).

The acceleration of freshly ionized material ("mass loading") exerts a drag on the surrounding plasma flow that consequently slows down. Field aligned currents couple the mass-loaded plasma to the giant flywheel Jupiter, the ultimate source of both pickup ("thermal") energy and kinetic energy of bulk corotational motion for the magnetospheric plasma. While the Jupiter flywheel is essentially an infinite source of momentum, the coupling mechanism is of limited efficiency. Three limitations potentially contribute to the poor coupling: insufficient transfer (via eddy diffusion) of momentum from Jupiter's lower atmosphere to the neutral atmosphere at ionospheric levels; insufficient collisional coupling between the neutral atoms and ions in the ionosphere (equivalent to low electrical conductivity); or a lack of electrons between the torus and ionosphere to carry the coupling currents. The relative importance of each of these three cases is an issue of current debate and research. In all scenarios the resulting sub-corotation varies primarily with the amount of mass loading in a given radial range.

One of major questions in Jupiter's magnetosphere is whether most mass loading happens in the near-Io interaction, or in the broad neutral clouds far from Io. There is no doubt that substantial pickup occurs near Io, based simply on the exposure of the upper atmosphere to pickup by the magnetosphere. Pickup near Io is also supported by evidence of fresh pickup ions of molecules (SO_2^+, SO^+, S_2^+, H_2S^+) near Io with dissociation lifetimes of just a few hours. But a closer look shows that the bulk of the Iogenic source comes from ionization of atomic sulfur and oxygen farther from Io. *Galileo* measurements of the plasma fluxes downstream of Io suggest that the plasma source from ionization of material in the immediate vicinity (within $\sim 5\,R_{Io}$) of Io is less than $300\,kg\,s^{-1}$ which is $\sim$15% of the canonical net ton-per-second Iogenic source (Bagenal, 1997; Saur *et al.*, 2003). The remainder must come from ionization of the extended clouds. It is not clear whether this was a typical situation nor well-established how much the net source and relative contributions of local and distant processes vary with Io's volcanic activity.

While most of the impacting plasma is diverted to Io's flanks, some is locked to field lines that are carried through Io itself. This $\sim$10% of upstream plasma is rapidly decelerated and moves slowly ($\sim$3–7 $km\,s^{-1}$) over the poles. Most of the particles are absorbed by the moon or its tenuous polar atmosphere so that the almost stagnant polar flux tubes are evacuated of plasma. Downstream of Io, the *Galileo* instruments detected a small trickle of the cold, dense ionospheric plasma that is stripped away. This cold, dense "tail" had a dramatic signature (>10 times the background density) but the nearly stagnant flow ($\sim 1\,km\,s^{-1}$) meant that the net flux of this cold, ionospheric material is at most a few per cent of the Iogenic source and is presumably quickly assimilated into the surrounding torus plasma.

11.5 COUPLING TO JUPITER'S POLAR IONOSPHERE

The presence of a volcanically active moon in the magnetosphere has significant effects on Jupiter itself. Io's electrodynamic coupling to Jupiter's polar ionosphere has been clear since the 1964 discovery that Io triggers Jovian radio emission. Studies over the past 40 years have revealed many clues but important specifics of this coupling process remain a puzzle. Figure 11.11 presents a simplified cartoon of the current picture.

Jupiter's radio emissions provide a strong but enigmatic set of clues to the interaction with the ionosphere. When Io lies at certain locations in its orbit relative to Earth, and Jupiter's magnetic field is near specific orientations relative to Io, decametric radio emissions are beamed toward Earth. These geometrical constraints led radio astronomers to conclude that the radio emission seems to be narrowly beamed along hollow cones (60–90° cone half-angle, with only $\sim$1.5° thickness), generated by electrons gyrating about the local magnetic field. It remains unclear what process actually generates the radio emission or why the radio emission is so tightly restricted along the edges of cones.

A second influence on Jupiter is evident in infrared and ultraviolet emissions from Jupiter's auroral zones (Clarke *et al.*, 2004). The precipitation of Iogenic particles into Jupiter's polar atmosphere causes observable emissions and significant chemical

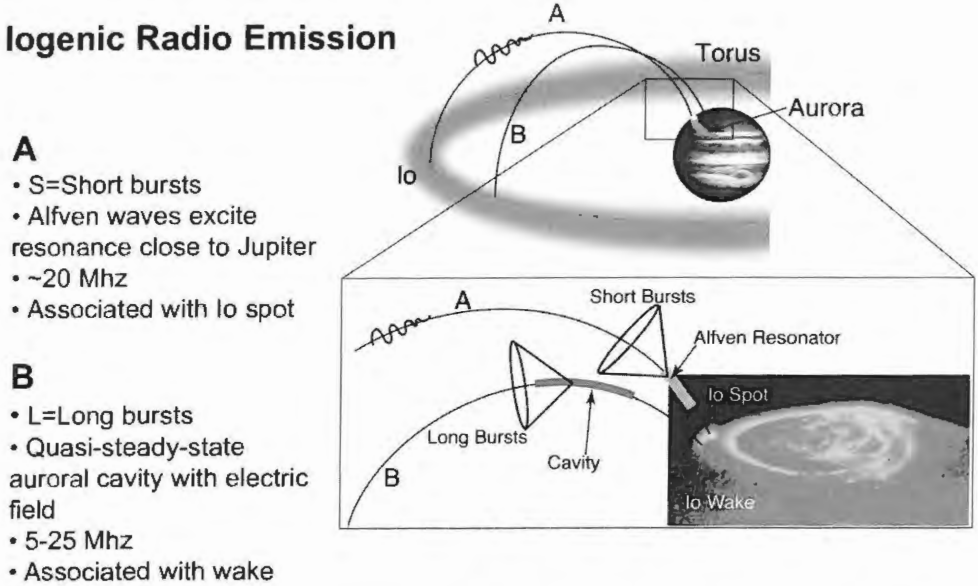

Figure 11.11. Geometry and mechanisms for Io-generated radio emissions from Jupiter's ionosphere. (See also color section.)

change, creating aerosols that darken the poles. While virtually all Jupiter's main aurorae are ultimately attributable material from Io spreading out through the magnetosphere, a particularly direct influence can be seen in the form of bright spots at the footprints of the flux tube that connects Io to Jupiter's ionosphere. Hubble ultraviolet images also revealed an extensive ultraviolet "wake" that started at Io's footprint and stretched half way around Jupiter. These auroral emissions indicate that substantial fluxes of electrons from Io are bombarding Jupiter's atmosphere. The question is how does Io generate these electron beams? An emerging picture begins to explain the basic features of both the radio and auroral emissions. The immense current flowing through Io's ionosphere couples to Jupiter's ionosphere via a direct, quasi-steady current loop just like a loop of wire. The current flowing along field lines deposits the energy that causes the ultraviolet and infrared emissions. Magnetic disturbances (Alfvén waves) caused by Io propagate along the same field lines and cause the radio emissions. Alfvén waves may excite a resonance close to the ionosphere of Jupiter, that may be responsible for short bursts of radio emission (S-bursts, lasting a few minutes) that seem to be emitted in the vicinity of the foot of the flux tube coupled to Io. Downstream of Io (leading Io in its orbit), longer bursts of radio emission (L-bursts, lasting ~2 hr) may be caused by Alfvénic disturbances that bounce between the ionosphere and the torus, or may be associated with currents that accelerate the newly picked up plasma toward corotation.

The major difficulty in describing the coupling between the Io interaction region and auroral phenomena is understanding how currents can flow in the low-density region between the plasma torus and Jupiter's ionosphere. Experience on Earth suggests that regions of strong electric field (sometimes called auroral cavities) develop which accelerate ions and electrons. It may be in such an auroral cavity region that the radio emissions are generated. Regions of electric field parallel to the magnetic field also allow the magnetospheric flux tubes to slip relative to the ionosphere. Our understanding of these high-latitude processes will remain entirely speculative until the *Juno* mission flies over the poles of Jupiter and measures the particles and fields in the auroral regions.

Iogenic plasma has broad influences in the magnetosphere as a whole. The outward diffusion of torus material creates a relatively dense and energetic plasma environment for the other Galilean satellites. Europa and Ganymede have measurable oxygen atmospheres created and lit up by the impact of Iogenic plasma, and Europa's trailing hemisphere is stained by the implantation of sulfur ions from Io.

In an even larger picture, Io's influence extends past Jupiter and into interplanetary space. Io's steady-state ton-per-second loss to the magnetosphere implies the same loss from the magnetosphere. Very little mass is lost to Jupiter itself, so most leaves the system entirely, either as fast neutrals (Figure 11.3) or plasma flowing out of Jupiter's magnetotail. The glow of fast neutrals can be seen to distances of one AU from Jupiter, and *Voyager* observations showed that Jupiter's magnetotail extends past Saturn.

In closing, Io's volcanic activity has profound and unexpected influences on its atmosphere, Jupiter's magnetosphere, the other Jovian satellites, and Jupiter itself. If the present loss rate of volcanic gases has persisted for the age of the Solar System, it means Io has shrunk at least 2 km, with the material escaping the Jupiter system entirely and ultimately being carried by the solar wind to the heliopause.

11.6 OUTSTANDING ISSUES

Despite the strong evidence for the basic picture presented here, many fundamental questions remain unanswered in the study of the neutral clouds, the torus, and magnetospheric interactions:

- How does the Iogenic source of plasma vary with volcanic activity on Io?
- What causes the variability – and stability – of the torus and neutral clouds?
- Is the "salt dust" emitted from Io of volcanic origin? How does it escape from Io?
- What creates the hot electrons apparently required to explain the state of the torus? Why is part of the hot electron population localized and sub-corotating?
- Where do currents actually flow near Io – ionosphere (conduction) or pickup?
- How much of the supply to the torus is picked up close to Io vs. far away?
- What is the feedback of the plasma interaction on Io's atmosphere?
- What is the nature of the coupling between Jupiter's ionosphere, Io, and the torus?
- How are radio emissions generated?

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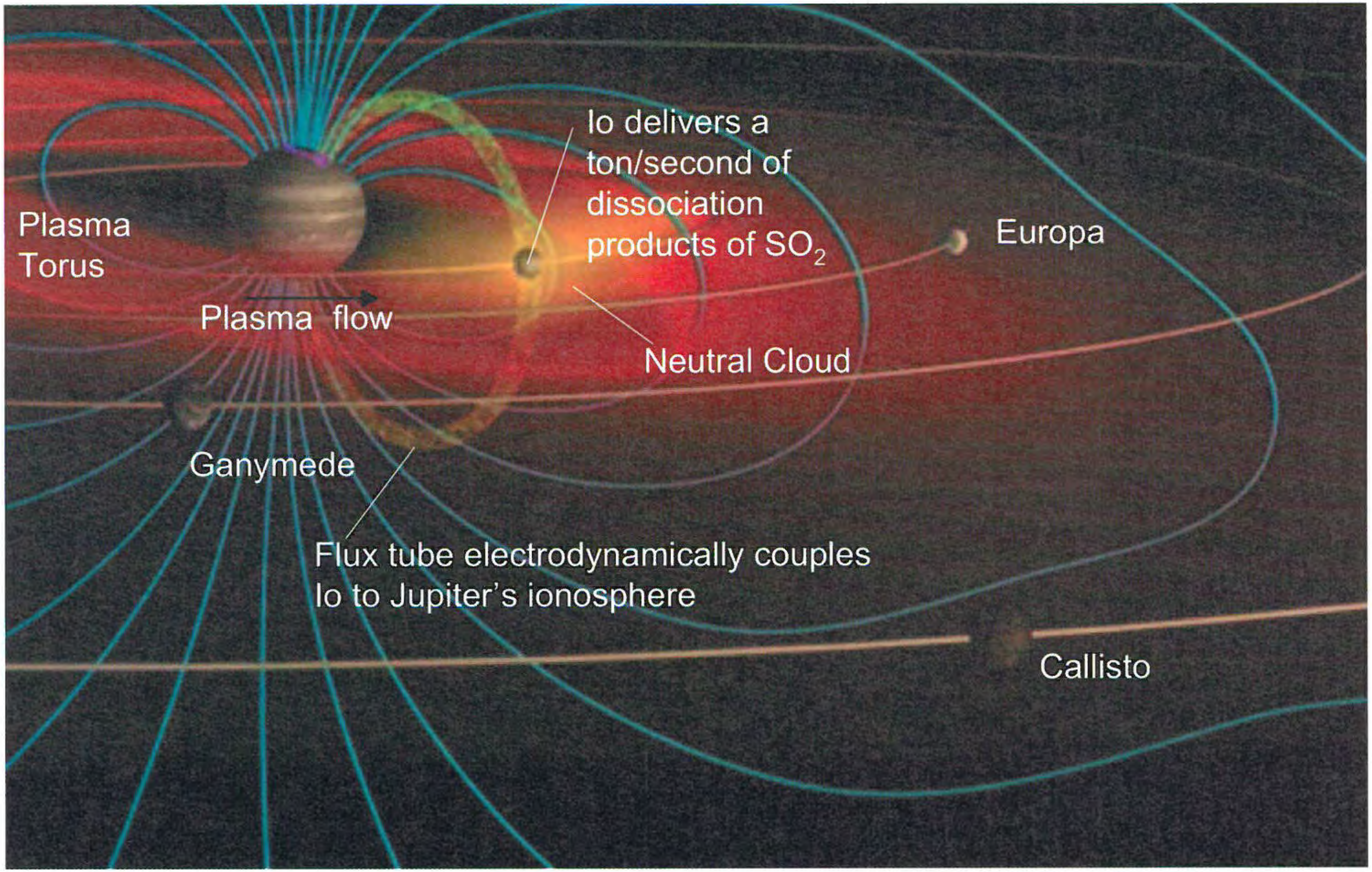


Figure 11.1. The main components of the Jupiter–Io system and their primary interactions.

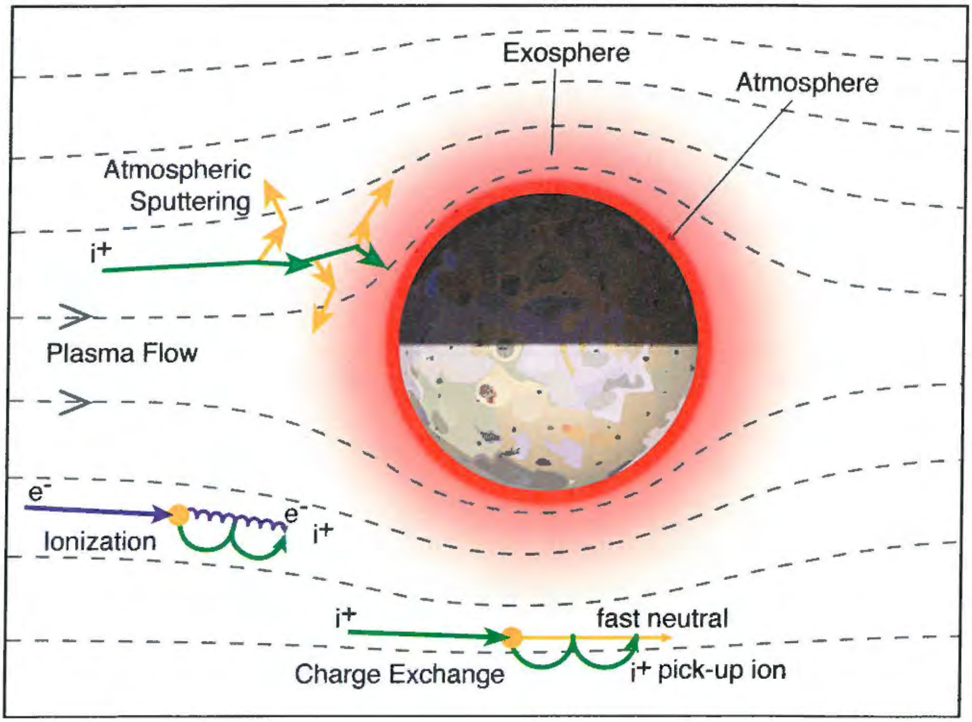
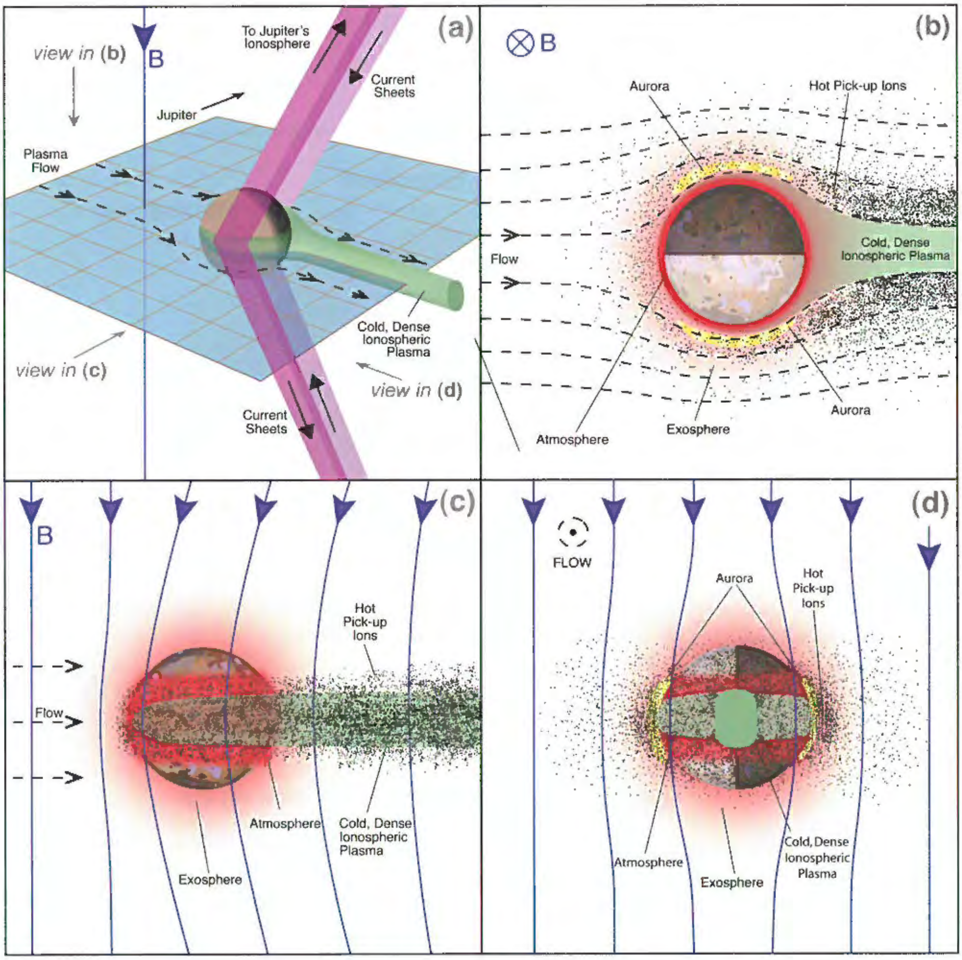


Figure 11.2. Important plasma/atmosphere interactions near Io. For simplicity the diagram shows the gyromotion for pick-up ions and electrons, but not for incident ions or electrons. The scale of the gyromotions has been greatly exaggerated: the gyroradius of a pick-up oxygen ion is 5 km, much less than Io's radius, and that of an electron is about 40,000 times smaller than the ion's.



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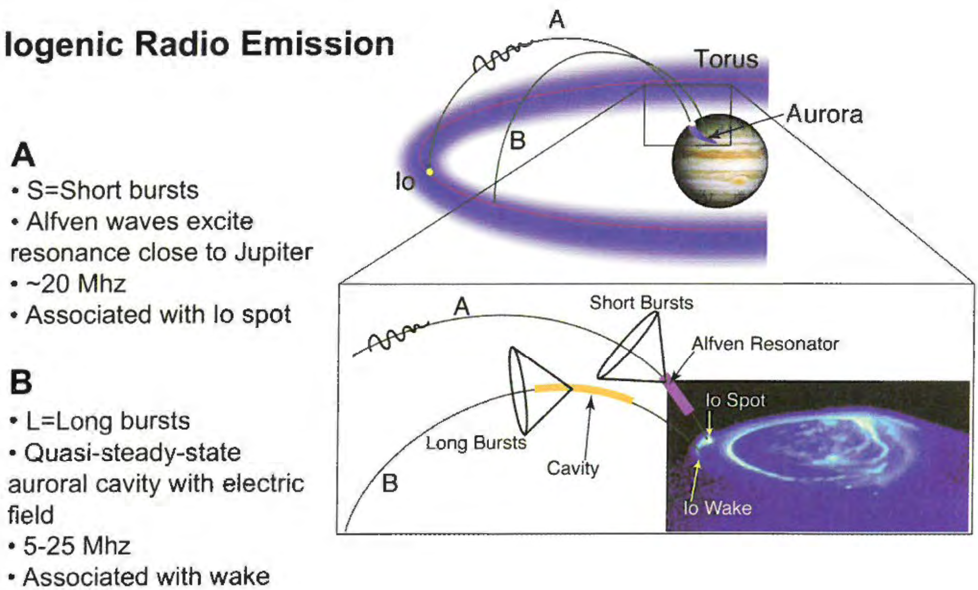

Figure 11.11. Geometry and mechanisms for Io-generated radio emissions from Jupiter's ionosphere.