The Space Environment of Io and Europa

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Key Points:

- \textit{Io, Europa substantially impact the jovian magnetosphere while interactions of plasma with moons affects their surfaces and atmospheres}
- \textit{Ten components are described, including neutrals, thermal plasma and energetic particles, spanning from Jupiter to interplanetary medium}
- \textit{Current understanding of the systems and processes are reviewed with a summary of outstanding questions}
Abstract
The Galilean moons play major roles in the giant magnetosphere of Jupiter. At the same time, the magnetospheric particles and fields affect the moons. The impact of magnetospheric ions on the moons’ atmospheres supplies clouds of escaping neutral atoms that populate a substantial fraction of their orbits. At the same time, ionization of atoms in the neutral cloud is the primary source of magnetospheric plasma. The stability of this feedback loop depends on the plasma / moon-atmosphere interaction. The purpose of this review is to describe the physical processes that shape the space environment around the two innermost Galilean moons – Io and Europa – and to show their impact from the planet Jupiter out into interplanetary space.

1 Introduction
In the 60s and 70s ground-based observations indicated Io was peculiar: the moon triggered radio emissions, appeared to brighten on emerging from eclipse, and optical emissions indicated clouds of sodium atoms and sulfur ions around Io. Further hints of Io’s peculiarity (specifically, its ionosphere) were indicated by Pioneers in 1973-4. Such strange behavior became more understandable when Voyager 1 and 2 flybys of Jupiter in 1979 revealed Io’s remarkable volcanism. The Voyagers also detected strong UV emissions from a torus of sulfur and oxygen ions surrounding Jupiter at Io’s orbit, and measured in situ the torus plasma. When Voyager 1 passed close to Io, perturbations in the plasma and magnetic field showed Io generating Alfven waves propagating away from the moon, carrying million-Ampere electrical currents along the magnetic field towards Jupiter. The Voyagers characterized a plethora of radio and plasma waves, several associated with Io or the Io plasma torus. Neither of the Voyager spacecraft passed close to Europa but distant images hinted at an intriguingly smooth, icy surface.

When the Galileo spacecraft went into orbit around Jupiter in 1995, close-up pictures of cracks, and a mysterious brown material on the surface made Europa a major focus of attention. Moreover, magnetic perturbations measured near Europa indicated an electrically-conducting liquid ocean under the ice. On several passes, the Galileo spacecraft also measured magnetic and particle perturbations near Io – as well as discovering that Ganymede has an internal magnetic field. In late 2000, the Cassini spacecraft got a gravity kick from Jupiter to accelerate its journey to Saturn. The Cassini UVIS instrument provided months of high-quality observations of the torus UV emissions, revealing the plasma composition and how the torus changed after a volcanic eruption on Io.

The aim of the 2004 monograph Jupiter: The Planet, Satellites and Magnetosphere (Bagenal et al. 2004) was to summarize the post-Galileo view of the jovian system. Chapters by Kivelson et al. (2004) and Saur et al. (2004) reviewed the current understanding of the electrodynamics of the plasma-moon interactions, and Thomas et al. (2004) reviewed Io’s neutral clouds and plasma torus, describing how ~1 ton/s of sulfur and oxygen escapes Io, becomes ionized and trapped in the magnetic field, and moves out to fill Jupiter’s vast magnetosphere.

In the meantime, while the Hubble Space Telescope (HST) and ground-based telescopes continue to observe the system, new measurements and models have emerged. In spring 2007 the New Horizons spacecraft got a gravity assist from Jupiter to speed its journey to Pluto, observing Io’s volcanism including an eruption of Tvashtar (Spencer et al. 2007; Rathbun et al. 2014;

The Juno spacecraft went into orbit around Jupiter in July 2016 (Bolton et al. 2017a). While the prime Juno mission does not bring the spacecraft inside Europa’s orbit, the particles and fields instruments are measuring the consequences of the Io-Europa space environment both out in the middle magnetosphere and close over the poles (Bagenal et al. 2017b; Bolton et al. 2017b; Connerney et al. 2017). Future missions to Europa further emphasize the need to consider the possible impacts that the changing environment near Io might have on the Europa system.

In past reviews the separate components of the Io-Europa system are generally discussed in isolation. To understand physical processes and the interconnections of the components, we need to look at the whole system. The goal of this review is to summarize the current understanding of this multi-component system and to present the outstanding questions. The remainder of Section 1 provides an overview of the system and a brief summary of what we know about the moons Io and Europa. In Section 2 we compare the atmospheres of these moons. In Section 3 we look at the interaction between these atmospheres and the plasma in which they are embedded. Section 4 describes the extended clouds of neutral atoms that come from the plasma-atmosphere interactions. The space environment between Io and Europa, the plasma torus, is reviewed in Section 5. Section 6 presents the evidence that these space environments spread their influence out into interplanetary space and into the atmosphere of Jupiter. Finally, we present a summary in Section 7, listing outstanding questions for future research. We have attempted to provide extensive references but also provide introductory and summarizing paragraphs without references to present a readable review that is accessible to a broad audience.

1.1 Ten Components of the Io-Europa Space Environment

Figure 1 shows the 10 main components of the system. Central to this picture are the moons Io and Europa. The interactions of the magnetospheric plasma with these moons’ atmospheres produce clouds of escaping neutrals that extend for a substantial fraction of Io’s and Europa’s orbits around Jupiter. Electron impact ionization of these neutral clouds produces the plasma that is trapped in Jupiter’s strong magnetic field. It is the intriguing feed-back systems between the moons and the magnetospheric plasma that begs understanding. The magnetospheric plasma primarily corotates with the planet’s 10-hour spin period, but also moves radially outwards over several weeks. About 10% of the torus material moves inwards from Io’s orbit. The flows inward of Io are about a factor 50 slower than the outward flow. As the majority of iogenic plasma moves out through the giant magnetosphere, it is heated to 10s-100s keV energies by an unknown process. Thus, while the lower-energy plasma moves outward and is heated, energetic electrons and ions (protons, sulfur and oxygen ions) move inward.

Charge exchange reactions between the corotating plasma and the neutral clouds produces energetic neutral atoms (ENAs with energies from a few hundred eV to a few keV) that escape Jupiter to form a neutral disk that extends 100s of R_J around Jupiter. Recent observations of heavy ions in Jupiter’s upper ionosphere by the Juno spacecraft suggest that some of the...
ENAs are also ejected inward and eventually hit the planet’s equatorial atmosphere to form a source of cold (ionospheric) heavy ions close to the planet.

When the very energetic (10s keV – MeV) ions from the middle magnetosphere move inward through the neutral cloud around Europa’s orbit, they charge exchange, making very energetic neutral atoms (vENAs with energies from a few 10s of keVs to MeVs). These vENAs have high speeds in all directions and likely spread into a huge sphere around the Jupiter system. Juno also detected an equatorial belt of energetic radiation close to the planet produced when the ENAs bombard Jupiter’s atmosphere (Kollmann et al. 2017).

This system of ten coupled components (listed in Figure 1) comprises a wide range of physics and extends from 10s of kilometers to Astronomical Unit scales.

1.2 Io and Europa: Bulk Properties

Io and Europa are similar in size to Earth’s Moon (Figure 2). Io, Europa and Ganymede are locked in a tight orbital resonance (with orbital periods increasing with distance from Jupiter by a factor of two) which drives tidal interactions between the moons (see review by Schubert et al. 2004). Tidal forces produce orbit-phase lock with Jupiter, so that when a moon is viewed from Earth, the surface longitude facing the observer and local time along the orbit are correlated. Consequently, we do not see much of the nightside of the moon. The strong dependence of tidal heating on radial distance, R, from the planet (1/R^6) explains why Io is the most volcanically active object and subsequently the densest moon in the solar system. Io emits ~10^{14} W internal heat, about 1/3 the solar heating (McEwen et al. 2004) and lost any water it may have had when formed. Io is covered with over 425 volcanic features (Figure 3). Of these, 50-100 are actively erupting at any one time, resurfacing the moon at a rate of ~1 cm/year, equivalent to the whole moon turning over ~40 times in 4.5 Ga (McEwen et al. 2004; Davies 2007; Lopes & Spencer 2007; Williams et al. 2011). A recent study of long term variations by de Kleer et al. (2019b) suggest Io’s volcanism may be modulated by periodic (~1.25 year) variations in orbital parameters. From Jupiter orbit, Juno’s Jovian InfraRed Auroral Mapper (JIRAM) instrument is taking spectacular infrared images of Io’s changing hot spots (Mura et al. 2020).

Europa’s bulk density of 3013 ± 5 kg m^{-3} is intermediate between that of Io (3528 ± 3 kg m^{-3}) and Ganymede (1942 ± 5 g cm^{-3}), suggesting it has lost much but not all of its primordial water, resulting in a mantle of ~80:20% rock:water composition (Anderson et al. 1996; Schubert et al. 2004). The magnetic field perturbations measured by Galileo on multiple flybys of Europa determined the presence of the water ocean (Khurana et al. 1998), supported by the presence of tidally-driven cycloidal fractures (Hoppa et al. 1999). The net tidal heating is less well known for Europa, ranging between 10^{12}-10^{13} W (Greenberg et al. 2002). Europa’s outer layer of water is equivalent to about twice the mass of Earth’s ocean, forming a 100-130 km layer capped by a 5-30 km ice layer (Cammarano et al. 2006; Vance et al. 2018). The depth:diameter ratio of the largest multi-ringed craters suggests penetration of the impactors through 19-25 km of ice (Schenk 2002). Geological features such as ridged plains, chaotic terrain, spreading bands, pits and domes suggest convection of ductile ice under a cold brittle surface (e.g., Schmidt et al. 2011). The major question that is driving future exploration of Europa (Pappalardo et al. 2013) is whether there are regions where the ice is thin or broken – spurred on by the detection of water plumes (Roth et al. 2014a,b; Sparks et al. 2016, 2017) – that might be places to search for evidence of life (Hand & Chyba 2007).
As discussed in the next sections, little of the surrounding energetic particles penetrate through Io’s atmosphere to reach the surface. Paranicas et al. (2003) report some fluxes of energetic electrons on the trailing side and polar regions might produce some detectable radiolytic products before they are covered up by SO2 frost (Carlson et al. 2007). However, a more recent of Juno data by Paranicas et al. (2019) found ~MeV electrons are very low close to Io likely due to losses by wave-particle interactions (Nenon et al. 2018) and not by collisions with Io. Additionally, the energetic ion environment near Io's orbit is strongly reduced, likely by wave-particles interactions and/or charge exchange. For our purposes this means that while many energetic particles can penetrate Io's atmosphere, these particles have very low flux near Io so are relatively unimportant for the surface. On the other hand, Europa’s thin atmosphere does little to protect Europa and the chemistry of exposed icy surfaces are likely altered by space weathering – some combination of delivering exogenic O and S plus radiolysis of surface ices (as reviewed by Paranicas et al. 2009, 2018).

Despite very different surface compositions (lava, sulfur, SO2 vs. water ice and brines/acids), Io and Europa have similar albedos (0.62 and 0.64 respectively) and similar average surface temperature of ~110 Kelvin (Rathbun et al. 2004, 2010a,b; Spencer et al. 1999). But the differences only increase as we look above the surface to their atmospheres.

2 Io and Europa Atmospheres

Io and Europa both have significant atmospheres but, like their surfaces, these atmospheres are very different in character (see Figure 4, Table 1, and references in sections 2.1, 2.2). McGrath et al. 2004’s review and references therein summarize the observations and modeling efforts available at the time. Io’s atmosphere is primarily due to sublimation of SO2 frost with some limited contribution of volcanic plumes. Europa’s atmosphere comes from charged particle sputtering of the icy surface producing H2O, O2 and H2 molecules. The water quickly freezes back onto the surface and hydrogen escapes, leaving Europa with an oxygen atmosphere. Io’s atmosphere is confined to low- to mid-latitudes with the polar pressures about 2% of equatorial pressures. Europa’s atmosphere is more uniform, with pressures comparable to the poles of Io. Remembering that Io and Europa are spin-phase locked and that the atmospheres are strongly affected by the plasma flowing from the orbit-trailing (upstream) side around to the orbit-leading (downstream) sides of the moons, one might expect variations with longitude. The sub-/anti-jovian longitudes (System III West) are 0°/180° while the leading/trailing longitudes are 90°/270°. Io has at least 16 active moderate to large plumes (Lopes & Williams 2015). To our present knowledge, Europa occasionally has an active plume. The role of these eruptions on each atmosphere is poorly known – but a keenly pursued research topic.

The total mass of Io’s atmosphere is about a hundred times that of Europa. This may not seem a huge difference, but, as we shall see in subsequent sections, the material escaping from Io’s atmosphere totally dominates the surrounding space environment.

2.1 Io’s Atmosphere and Corona

Io’s atmosphere is still surprisingly poorly known. Some atmospheric properties (density, composition, asymmetries, equatorial extension) have been observed via telescopes on the ground, Earth orbit or several spacecraft at Jupiter. Some atmospheric properties have also been deduced from in-situ plasma observation and numerical modeling of the plasma-atmosphere
interaction. From these observations, it is concluded that Io has a collisionally-thick SO$_2$ atmosphere with a surface pressure of 1-10 nbar, concentrated ±40° of the equator (see reviews by McGrath et al. 2004; Lellouch et al. 2007).

Earth-based telescopes provide important information about the dayside atmosphere from UV to millimeter wavelengths. These remote observations consist of brightness integrated along the line of sight on the sunlit hemisphere of Io. They provide an estimate of the column density on the dayside atmosphere but they give limited information on its radial extension or variations with time of day. Io’s surface pressure is primarily controlled by the sublimation of SO$_2$ frost (Tsang et al. 2012, 2013a,b, 2016; Lellouch et al. 2015), which is supported by the fact that the atmospheric column density drops by a factor of 5 ± 2 after 40 minutes of eclipse (Tsang et al. 2016; Retherford et al. 2007, 2019). The atmospheric density above the poles is just ~2% of the equatorial density (Feaga et al. 2009, Strobel and Wolven 2001; Lellouch et al. 2015). This distribution is likely primarily caused by the equatorial distribution of the frost on the surface and its preferential heating at the sub-solar point, but also by the location of some of the main volcanoes at low latitude. The vertical column density at the equator ranges from 1.5 x 10$^{16}$ cm$^{-2}$ at sub-jovian longitudes to 15 x 10$^{16}$ cm$^{-2}$ at anti-jovian longitudes (Feaga et al. 2009; Jessup et al. 2004; Spencer et al. 2005; Lellouch et al. 2015). The anti-jovian atmosphere is not just denser but also latitudinally more extended than the sub-jovian side (Feaga et al. 2009).

Radio occultations of Io’s ionosphere both with Pioneer 10 and Galileo supported the existence of a substantial atmosphere. Pioneer 10 radio occultations revealed a dense ionosphere with a peak density ~ 60,000 cm$^{-3}$ at ~ 100 km altitude on the dayside (Hinson et al. 1974; 1976), comparable to ionospheres of Mars and Venus. The nightside ionosphere appeared less dense. Six radio occultations were performed by Galileo in 1997 (Hinson et al. 1998). The ionosphere appears asymmetrical with the plasma density depending strongly on Io’s longitude. The interpretation of the observations assumes that the increased plasma density is distributed in a spherically symmetrical bound ionosphere with a dense downstream wake. Depending on location, peak densities of at least~ 50,000 cm$^{-3}$ were found, reaching a maximum of ~ 250,000 cm$^{-3}$ in one of the occultations. The asymmetries of the ionospheric densities are not surprising considering the many parameters that influence the ionization process (electron deflection by electromagnetic interaction, electron cooling by interaction with molecules, electron beam ionization in the wake). It is notable that numerical simulations of the plasma/atmosphere interaction do not usually reproduce electron density as high as ~ 100,000 cm$^{-3}$ (Saur et al. 1999; Dols et al. 2011) but interpretation of the observations presents many uncertainties (accurate spacecraft trajectory, presence of active hotspots, etc.) and limitations (entry and exit points of the occultations are always at the terminator, assumption of a spherical symmetry of the bound ionosphere).

The sublimation/condensation response of the atmosphere to day/night/eclipse variations was modeled by Moore et al. (2009) and Walker et al. (2010, 2012) who showed that, on the dayside, most of the atmospheric column is probably contained in the first 200 km with a steep density profile under 20-30 km. The nightside atmosphere of Io is poorly constrained. The low temperatures at night would suggest SO$_2$ condenses onto the surface and the composition of the atmosphere changes drastically. Walker et al. (2010) results show a drop of column density from the peak density on the sunlit hemisphere to the night atmosphere by a factor 100-1000 (in their base case), but these simulations depends on many parameters that are still poorly constrained. The possibility of non-condsensible components (e.g. O$_2$) on the nightside of Io was first
suggested by Kumar (1982). Modeling by Wong and Johnson (1996) indicate that the nightside atmosphere may be dominated by non-condensable gases (O₂ and possibly SO) with SO₂ condensing onto the surface. Moore et al. (2009) show that a buffer could be created by even a small amount of non-condensable gases close to the surface, limiting the condensation of SO₂. On the other hand, Lellouch et al. (2015) report that the column density changes by a factor of ~2 before and after noon corresponding to sublimation driven by ±2 Kelvin change in temperature. Furthermore, the factor 5 ± 2 collapse (40 min into the 2-hour eclipse) observed by Tsang et al. (2016) indicates that the effect of non-condensable gases is small. The data are currently very limited but it is reasonable to assume that the atmosphere is significantly less dense on the nightside of Io but probably does not completely condense out.

SO₂ comprises 90% of the surface atmospheric pressure. Atmospheric SO was detected in mm-wave observations at the 3-10% level (Lellouch et al. 1996; Mouillet et al. 2010, 2013; deKleer et al. 2019a). But the global coverage and column density of SO are uncertain. There are reports of minor species (KCl by Mouillet et al. 2003, NaCl by Lellouch et al. 2003) that are likely linked to volcanic outgassing and Spencer et al. (2000) reported enhancement of S₂ over the Pele volcanic plume. From modeling the photochemistry of the atmosphere, Moses et al. (2002a) suggest the SO/SO₂ and S/O ratios may increase during more volcanically active epochs.

Deep in Io’s atmosphere photodissociation plays important roles, while higher up in the atmosphere, electron collisions are more important. Photodissociation of molecular species within ~5 hour time frame means that the dayside atmosphere will have a higher atomic composition (O, S, Na) than the nightside concentration (Moses et al. 2002a,b). Post-eclipse brightening of sodium emissions suggest that photodissociation of the volcanically-produced NaCl accounts for most of the atomic sodium produced by Io (Grava et al. 2014).

The Io atmosphere also has a remarkable high-altitude component of atomic species: S and O (Wolven et al. 2001). There is a corona within Io’s Hill sphere (~5.8 RIo) as well as neutrals that escape Io’s gravity and extend partly around Io’s orbit. While O is observed in both visible and UV, there has only been sparse detection of S in the UV (Durrance et al. 1995; Ballester et al. 1987; Wolven et al. 2001). Auroral emissions of O and S are produced by electron impact excitation of the neutral atmosphere (Roesler et al. 1999; Retherford et al. 2000, 2003; Geissler et al. 2001, 2004). It is commonly accepted that the emissions are primarily caused by thermal (5 eV) electrons impacting O. The emissions depend on the neutral density as well as the electron density and temperature (including the supra-thermal population for UV emissions), all of which are thought to vary drastically in the environment close to Io. The relative importance of each electron property as well as the neutral density can only be estimated through numerical simulations of the plasma/atmosphere interaction (see Section 3.1). The S and O auroral emissions display several structures: Two large elongated equatorial spots on Io’s flanks (Roesler et al., 1999; Retherford et al. 2000; 2003), further emission downstream along the flanks of Io at low altitude (Roth et al. 2011, 2014a,b), a coronal emission that extends smoothly to ~10 RIo from the surface (Wolven et al. 2001; Retherford et al. 2019), and polar limb brightening over the pole that faces the plasma sheet during the diurnal rotation of Jupiter (Retherford et al. 2003). The density profiles of O and S in the atmosphere are still not well known. From modeling of the interaction and its resulting O and S emissions, the O/SO₂ ratio is estimated to be between 10-20% in the upper atmosphere (the models do not resolve the deep
atmosphere) and S/SO₂ ~ 1.5% with a scale height slightly larger than SO₂ (Feaga et al. 2009; Roth et al. 2011, 2014a,b).

In summary, the atmosphere of Io is mostly sublimation-controlled SO₂, with a vertical column of SO₂ ranging from 1.5 to 15 x 10¹⁶ cm⁻², concentrated around the equator. Active volcanic plume atmospheres likely have a more important role on the nightside and polar hemispheres. Extending far from Io’s surface are minor species S and O, that form a tenuous corona stretching to distances of ~10 R₉. There are still major uncertainties about the radial profile, longitudinal asymmetries, minor species composition and how much the atmosphere collapses at night or in eclipse.

2.2 Europa’s Atmosphere

The existence of an atmosphere at Europa is supported by the observation of UV aurora in atomic oxygen lines as well as the detection of an ionosphere by radio occultation. As at Io, properties of the global atmosphere are also inferred from numerical simulations of the plasma-atmosphere interaction, constrained by Galileo plasma observations (see Section 3.2). Europa’s atmosphere is tenuous (surface pressure ~3 pbar), only collisional near the surface, and mainly composed of O₂ that is fairly uniformly distributed over the moon (see reviews by Johnson et al. 2009, 2019; McGrath et al. 2004, 2009; Burger et al. 2010; Coustenis et al. 2010; Plainaki et al. 2018).

UV auroral emission of Europa’s atmosphere in the 130.4 and 135.6 nm oxygen lines are observed with the Hubble Space Telescope (HST). These UV emissions of oxygen atoms are consistent with electron impact dissociation of an O₂ atmosphere with vertical column density of 2-15 x 10¹⁴ cm⁻² (Hall et al. 1995, 1998; McGrath et al. 2009; Saur et al. 2011; Roth et al. 2014a,b). The UV emissions depend on the neutral density, as well as on the electron density and temperature. Thus, deriving neutral densities and their distribution is difficult and requires numerical simulations (Saur et al. 1998). The extensive analysis of the O aurora by Roth et al. (2016) argues for a more limited range of 2-10 x 10¹⁴ cm⁻². The O brightness is similar in daylight or in eclipse showing that the atmosphere does not collapse at night like at Io (because O₂ is non-condensable). Unlike Io, the main auroral emissions are not on the flanks but above the pole, and specifically brighter on the polar hemisphere facing the plasma sheet. It is concluded that, in contrast to Io, Europa’s atmosphere extends more uniformly from pole to pole (see Figure 4).

The presence of an extended atomic O corona is supported by Cassini UVIS observations during its Jupiter flyby (Hansen et al. 2005) and HST observations in UV (Roth et al. 2014a,b; 2016). The resulting picture is an O₂-dominated atmosphere up to 900 km (1.6 R₉) where the O mixing ratio varies from 6% to 30%. De Kleer & Brown (2018) measured optical emissions in Europa’s atmosphere (dominated by electron impact dissociation of O₂ leaving atomic products in an excited state) and concluded that the global O/O₂ ratio is less than 35%. Roth et al. (2017a) detected an atomic hydrogen corona with the HST. They estimate a surface density of H to be ~2000 cm⁻³ and thus a number density mixing ratio at the surface of ~0.001%.

Erupting plumes may also contribute water vapor to the atmosphere. They are observed in O lines and H-Lyman alpha lines (Roth et al. 2014a,b) and in absorption during Jupiter transit (Sparks et al. 2016, 2017). Paganini et al. (2019) report sporadic water vapor emissions,
attributed to plumes, detected in H$_2$O infrared fluorescent lines in bulk across the surface. But these detections seem rare with only one positive detection out of 16 observations.

The effect of these plumes on the Galileo plasma and magnetic field observations during low altitude flybys is reported by Jia et al. (2012) and Arnold et al. (2019). Longitudinal asymmetries in the aurora brightness are observed but their interpretation in terms of inhomogeneity of the atmosphere is unclear. Roth et al. (2016), in a compilation of many observations at different Europa orbital longitudes, shows that the dusk hemisphere is always brighter than the opposite hemisphere. This asymmetry of the auroral brightness is attributed to a local denser atmosphere caused by not only the potential presence of plumes, but also ice thermal inertia (Plainaki et al. 2013) or the effect of Europa’s varying illumination (Oza et al. 2018, 2019). Oza et al. (2018) argues that the dawn-dusk asymmetry could not be reproduced with just a sputtered (trailing hemisphere) source and that an additional sub-solar source is needed, which Johnson et al. (2019) tentatively identified as thermal desorption of O$_2$ from the regolith. But Roth et al. (2016) suggests that some of these brightness asymmetries could also result from the variation of the plasma interaction. Rathbun & Spencer (2020) used Galileo PPR data (1996-1999) plus Earth-based observations from ALMA by Trumbo et al. (2017) to look for thermal emission at the locations of plumes reported by Sparks et al. (2017) and Jia et al. (2012) but found “there is nothing in the PPR and ALMA data investigated that provides supporting evidence for plumes or plume deposits at either of these locations on Europa.”

The degree of upstream/downstream asymmetry of the atmosphere is not very clear. Pospieszalska and Johnson (1989) modeled the sputtering of Europa’s surface and show that the sputtering flux is not uniformly distributed and peaks at the trailing hemisphere. But there is little observational support for this. The oxygen auroral brightness is slightly lower on the leading hemisphere compared to the trailing, which is interpreted as a global atmosphere distributed upstream and downstream (Saur et al. 2011; Roth et al. 2016). The Kliore et al. (1997) non-detection of an ionosphere on the downstream hemisphere was interpreted as largely due to a lack of ionization rather than a lack of atmosphere.

The source of the atmosphere is the sputtering of ions (thermal and hot) and maybe high-energy electrons on the icy surface of Europa. Lab experiments of ion bombardment of water ice (Fama et al. 2008) suggests that H$_2$O molecules are the dominant ejecta when magnetospheric ions hit Europa’s surface. Molecules of O$_2$ and H$_2$ are also sputtered off the icy surface. Molecular oxygen, O$_2$, probably dominates the atmosphere because it neither freezes to the surface like H$_2$O, nor quickly escapes Europa’s gravity like H$_2$ (Johnson et al. 1982; 2009).

There is no consensus on the relative contributions of thermal ions versus energetic ions to the production of the O$_2$ atmosphere (Mauk et al. 2004; Paranicas et al. 2009). Cassidy et al. (2013) show that thermal heavy ions (S, O at 1-2 keV ram energy) could be responsible for supplying the atmosphere. They estimate the O$_2$ and H$_2$ production rates by multiplying the ion flux with the sputtering yields for O$_2$. The yields are functions of the ion kinetic energy and are provided by Teolis et al. (2010, 2017). The ion flux was calculated very simply, ignoring the electromagnetic interaction that diverts the plasma flow around the moon and shields its surface. Other processes could contribute to the atmosphere production. Ip (1996) proposed that ionization creates O$_2^-$ ions which, when accelerated by local electric fields, could cause significant sputtering. But Saur et al. (1998), based on plasma-atmosphere simulations, suggested that these picked-up ions are too slow for efficient sputtering. Both Dols et al. (2016) and Luchetta et al. (2016) argue that charge exchange reactions between in-coming ions and the
Neutral atmosphere are key. Dols et al. (2016) proposed that fast neutrals resulting from multiple
charge exchange reactions between pickup O$_2^+$ ions and atmospheric O$_2$ provide supplemental
sputtering. But the sputtering rate of these fast neutrals has yet to be well quantified.

Six radio-occultations of the Galileo spacecraft by Europa were performed between 1996
to 1997 (Kliore et al. 1997). They revealed the existence of a tenuous ionosphere with an average
electron density ~9,000 cm$^{-3}$ with an ionospheric scale height ~240 km close to the surface. This
scale height is consistent with later observations of the O auroral emissions (Roth et al. 2016)
and numerical simulations (Saur et al. 1998). These observations supported the existence of a
neutral atmosphere with a vertical column density $\sim$0.7-3.6 x 10$^{15}$ cm$^{-2}$ and a neutral scale height
~ 120 km. It is notable that the location of the strongest among the positive ionospheric
detections ($\sim$13,000 cm$^{-3}$) roughly coincides with a reported plume feature and thermal anomaly
identified in Galileo thermal imaging (McGrath & Sparks 2017).

In contrast to Io, it is remarkable that no ionosphere was detected near the middle of the
wake region. This absence of a plasma wake suggests an absence of ionization, rather than an
absence of atmosphere.

In summary, Europa’s tenuous, global atmosphere is still poorly constrained by
observations. We await better measurements of the number and frequency of the sporadic plumes
but their contribution to the global atmosphere seems to be limited. The source of the atmosphere
is primarily particle sputtering of the icy surface but a comprehensive model of the atmosphere is
still lacking.

3 Plasma-Satellite Interactions

Figure 5 illustrates the main components of plasma-satellite interactions, Figure 5a
presenting the basic geometry. Figure 5b indicates some of the chemical reactions as the plasma
impacts the atmosphere. Figures 5c and 5d show the UV and radio emissions excited at Jupiter
by streams of electrons that are generated by the plasma-satellite interactions. Below we provide
the historical context of indications of satellite-driven processes far from the moons. But the
primary focus of this review is what is happening at Io and Europa.

Before the 1958 Explorer 1 discovery of Earth’s Van Allen radiation belts, bursts of radio
emission revealed Jupiter has a magnetic field that traps electrons (Burke & Franklin 1955).
High frequency synchrotron emissions were discovered by Drake and Hvatum (1959). These
high frequency (GHz or decimetric wavelength) radio emissions come from the MeV electrons
trapped close (<2.5 R$_J$) to Jupiter (reviewed by Bolton et al. 2004). The bursts of emission at
decametric wavelengths (few-40 MHz) showed modulations with Jupiter’s spin period and, to
great surprise, the orbital phase of Io (Bigg 1964). The Io modulation of radio bursts triggered
ideas of an electrically-conducting Io acting like a generator as it moved relative to Jupiter’s
magnetic field (a “unipolar inductor”), driving electrical currents that complete a circuit between
the moon and the planet’s ionosphere (Marshall & Libby 1967; Piddington & Drake 1968;
Goldreich & Lynden-Bell 1969). The radio emissions indicate processes close to the planet,
involving electrons radiating as they move along the magnetic field away from Jupiter, and say
little about the generation mechanism at Io. On 6 March 1979 Voyager 1 flew past Io where the
instruments detected plasma and magnetic field perturbations consistent with a packet of Alfvén
waves forming an Alfvén wing propagating from Io (Belcher et al. 1981; Acuna et al. 1981). The
Voyager observations provoked theoretical models by Goertz (1980), Neubauer (1980), and Southwood et al. (1980). Gurnett & Goertz (1981) suggested that multiple ionospheric reflections of such Alfvénic disturbances between north and south hemispheres of Jupiter (Figure 5d) could produce the pattern of arcs in the frequency-time spectrograms of the Voyager Planetary Radio Astronomy instrument (Warwick et al. 1979). As Earth-based telescopes improved, auroral emissions in Jupiter’s atmosphere – IR, UV, – revealed features at first associated with Io (Connerney et al. 1993; Clarke et al. 1996; Prange 1996), and then not just Io but also Ganymede, Europa (Clarke et al. 2002; Grodent et al. 2006; Bonfond et al. 2017a,b) and, recently, Callisto (Bhattacharyya et al. 2018). These auroral emissions (Figure 5c) indicate that the plasma-satellite interactions all involve electrodynamic perturbations, which generate Alfvén waves propagating from the moon, carrying electric currents parallel to the magnetic field, accelerating electrons that bombard Jupiter’s atmosphere and generate auroral emissions. The Juno mission is revealing new details about these auroral emissions and flying through the polar end of the fluxtubes that couple to the moons (Mura et al. 2018; Szalay et al. 2018, 2019; Hue et al. 2019; Paranicas et al. 2019).

Close to the moons, the interactions of the jovian plasma with moon atmospheres produce large perturbations of the magnetic field and local plasma properties (flow velocity, density, temperature and composition). Over 33 orbits of Jupiter, the Galileo spacecraft made several close passes of Io and Europa where the particles and fields instruments measured the local perturbations (summarized by Kivelson et al. 2004). Table 2 summarizes the range of plasma conditions upstream of Io and Europa.

Saur et al. (1998) propose an estimate of the relative strength of the interaction at the moons as the ratio of the ionospheric electric field to the corotation electric field (called \( \alpha \)). This ratio is based on the calculation of the Alfvén, Pedersen and Hall conductances of the moons’ ionosphere (see also Southwood et al. 1980). It is a quantitative estimate of the divergence and slowing of the flow around the moon’s ionosphere: \( \alpha = 0 \) corresponds to the case of no electrodynamical interaction (plasma interaction with an insulating moon) where the plasma impinges, undiverted, on the moon’s surface, while \( \alpha = 1 \) corresponds to the strongest interaction (the moon as a perfect conducting body) where the plasma is fully diverted around the moon by the electrodynamic interaction and does not reach the surface. The interaction at Io is stronger than at Europa, with \( \alpha \sim 0.96 \) for Io when it is located in the center of the torus and \( \sim 0.8 \) for Europa (Saur et al. 2013)

When looking at the plasma conditions listed in Table 2 and the strength of the interaction (\( \alpha \)), we note that the atmosphere/plasma interaction is intrinsically time-variable for two main reasons. The first is the inclination of the torus centrifugal equator by 7° relative to Io’s orbital plane (further discussed in section 5). During a jovian synodic period (13 hours at Io and 11 hours at Europa), the moons experience variable upstream plasma densities and thus, a variable strength of the interaction. Secondly, the moons’ atmospheres are also variable depending on the atmospheric sources. At Io, the SO₂ atmosphere is primarily sublimation-supported, varying with illumination and when there are particularly strong volcanic eruptions. For Europa, the atmosphere results from sputtering of the surface by thermal and energetic ions but the O₂ desorption from the icy surface seems to depend on illumination as well (Johnson et al. 2018, 2019). Thus, the atmospheric column and the interaction’s strength depend on the illumination of the hemisphere impacted by the torus plasma.
In Figure 5b, the impact of thermal electrons on the neutral atmosphere is the main local source of new ions (called “mass-loading”), which are mostly molecular (SO$_2^+$ at Io and O$_2^+$ at Europa). Photoionization represents only ~10-15% of the total ionization rate (Saur et al. 1998, 1999). A molecular atmosphere is very efficient at cooling the impinging thermal electrons (Saur et al. 1998, 1999; Dols et al. 2008, 2012, 2016) via ionization and dissociation of molecular neutrals and also by exciting molecular electronic, vibrational and rotational levels. These cooling processes are so efficient that the primary electrons would rapidly become too cold to provide any further ionization if they were not replenished by the content of the flux tube above and below the moon.

Ion charge exchange processes (asymmetrical and resonant) do not provide new charge density but they can change the ion composition and constitute an important sink of momentum for the upstream plasma (called “momentum-loading”). After an ionization or a charge exchange reaction, the new ion is initially at rest in the frame of the moon. It is then “picked up” by the background bulk plasma flow and also starts a gyro-motion at the local flow velocity (further discussed in Section 5.1). The pickup process also affects the average ion temperature of the plasma. Depending on the location of this pickup, the local flow velocity is larger than the upstream velocity (on the flanks) or smaller (in the deep atmosphere) and the pickup process is either a gain or a loss of energy that affects the average ion temperature. For instance, an SO$_2^+$ ion picked up by a 60 km/s flow at Io will gain 1080 eV, which represents a net heating of the upstream plasma (with a typical temperature of ~100 eV). In Figure 5b, the ion/neutral process called “atmospheric sputtering” refers to ion/neutral elastic collisions without exchange of charge and after multiple collisions, a neutral is finally ejected from the atmosphere (McGrath & Johnson 1987). The resulting neutral clouds are discussed in section 4.

The pickup (of newly ionized and charge-exchange products) and collision processes both slow the plasma flow close to the moon and divert some of the plasma around the flanks as illustrated in Figure 5. To first approximation, the magnetic field is frozen to the plasma flow (outside of the conducting ionosphere). Thus, any flow perturbation also produces large magnetic field perturbations that propagate away from the moon in the three classical MHD wave modes (fast, slow and Alfven). In particular, the magnetic perturbation propagates along field lines as Alfven waves towards the ionosphere of Jupiter (Acuna et al. 1981) and forms a stationary structure in the reference frame of Io called an Alfven wing (Goertz et al. 1980; Neubauer 1980; Belcher 1987). A large current is carried along this Alfven wing (~3 MAmp for Io, according to Acuna et al. 1981). The plasma flow is diverted not only around the solid body of the moon but also around the entire Alfven wing extending from Io to the ionosphere of Jupiter (see Fig 21.2 in Kivelson et al. 2004).

Approaches to modeling these complex plasma-moon interactions range from focusing on the electrodynamics with limited chemistry to assuming simple electrodynamics and focusing on the chemistry. Figure 6 illustrates an example of the latter approach for the Io case. A similar approach can be taken for Europa, with appropriate modification of the atmosphere and upstream plasma. Numerical simulations of this interaction are constrained by in-situ observations of the plasma properties close to the moons (Voyager and Galileo) and by remote observations of the moons’ auroral emissions. Beyond matching the observations, the modeling approach allows an exploration of the main features of the interaction. Numerical simulations by Linker et al. (1998) and Combi et al. (1998) illustrate the generation and propagation of the three MHD wave modes. Numerical simulations (e.g., Saur et al. 1998, 1999, 2002, 2003; Dols et al. 2008, 2012, 2016;
Blocker et al. 2016, 2018; Rubin et al. 2011; Lipatov et al. 2010, 2013; Sebek et al. 2019), reveal the relative importance of each plasma process (ionization, charge-exchange, collision), constrain the neutral atmosphere distribution radially and longitudinally, estimate the local plasma production and neutral loss, and explore the presence of an induced magnetic field either in Io’s asthenosphere (Khurana et al. 2011) and/or core (Roth et al. 2017b), or in a subsurface ocean for Europa (Zimmer et al. 2000; Schilling et al. 2007, 2008), plus test evidence for plumes (Blocker et al. 2016; Jia et al. 2018; Arnold et al. 2019).

While the physical processes (Figures 5, 6) are similar at Io and Europa, there are major differences. Below we describe each interaction separately and then make a comparison in section 3.3.

3.1 Plasma-Io Interaction

The Galileo spacecraft made 5 flybys of Io between 1995 and 2001 revealing very strong plasma and field perturbations. The relative velocity of the torus plasma in Io’s frame is ~60 km/s. The plasma is mainly composed of S++ and O+ ions at temperatures of ~100 eV. The gyroradius of the thermal ions is ~2 km and the gyrofrequency is ~1.5 Hz (see Table 2). When Io is in the centrifugal plane of the torus, the flow is quasi-stagnated at the point where the plasma impinges on the atmosphere, with 95% of the plasma diverted around the flanks. The electron flow close to Io is strongly twisted towards Jupiter because of the Hall conductivity of the ionosphere (Saur et al. 1999). The magnetic perturbation reaches ~700 nT in a background field of ~1800 nT (Kivelson et al. 1996a). Downstream of Io, Galileo detected a wake of plasma that was very dense (~30,000 cm^{-3}), very slow (flow speed <1 km s^{-1}) and very cold (T_i ~ 10 eV) (Frank et al. 1996; Bagenal 1997). Bi-directional parallel electron beams above the poles and in Io’s wake were also detected with an energy ranging from ~140 eV to several 10s keV (Frank and Paterson 1999; Williams et al. 1996, 2003; Mauk et al. 2001). Finally, Electro-Magnetic Ion Cyclotron (EMIC) waves were observed far downstream of Io at the SO_2+ and SO+ ion gyro-frequencies, suggesting a pickup process far (>10 R_{Io}) from Io (Warnecke et al. 1997; Russell & Kivelson 2000; 2001).

The local auroral emissions provide additional constraints on the atmospheric distribution, composition and plasma interaction, including during eclipse. Saur et al. (2000) and Roth et al. (2011) have modeled the plasma atmosphere interaction at Io, constrained by the oxygen auroral emissions. Roth et al. (2014c) propose a phenomenological model of the structures of the auroral emissions, based on observations gathered from 1997 to 2001.

They conclude that during this 4-year period, the auroral emissions did not vary beyond the changes of the periodically varying local environment caused by the latitudinal motion of Io in the torus. This stability is remarkable considering the potential variation of Io’s atmospheric content caused by sporadic major volcanic eruptions during such a long period. Furthermore, Roth et al. (2017b) argue that the rocking of Io’s auroral spots is consistent with induction in the deep iron core rather than shallow asthenosphere as proposed by Khurana et al. (2011). Blocker et al. (2018) supported Roth’s idea by claiming that most of the magnetic field perturbation observed during Galileo flybys were caused by an asymmetric atmosphere and not by a strong induction signal.

In Figures 7, 8 and 11, we illustrate the plasma-neutral interaction at Io using the multi-species chemistry approach sketched in Figure 6. Although the model results vary with the
assumptions of the simulation, they provide reasonable estimates of the contribution of each process and the resulting plasma properties. The simulations presented here are 2D simulations in the equatorial plane of Io similar to Dols et al. (2008). They are a mixture of material already published and new unpublished simulations.

The main assumptions and results are summarized below. The plasma flow is prescribed as an incompressible flow around a conducting obstacle. The simulation shown in Figure 7 does not include the parallel electron beams detected by Galileo. These parallel electron beams probably provide much of the ionization in the wake, particularly when a dense atmosphere is present (Saur et al. 2002; Dols et al. 2008). Figure 7 shows the plasma properties in the equatorial plane of Io. The SO2 distribution is assumed cylindrically symmetrical and thus does not include any day-night asymmetry resulting from a collapse of the SO2 atmosphere at night. The radial distribution is based on Saur et al. (1999). These authors propose a radial hydrostatic atmosphere with a surface scale height of 100 km, vanishing at a distance of 3.5 RIo above the surface. The resulting vertical column at the equator (6 x 10^{16} cm^{-2}) is consistent with dayside observations. To account for the equatorial distribution of the SO2 atmosphere (Strobel and Wolven 2011) in this 2D approach, we assume that the SO2 atmosphere extends 1 RIo perpendicular to the equatorial plane. The S and O atmosphere is assumed to be spherically symmetric based on the UV emission radial profiles of Wolven et al. (2001).

The plasma flow is slowed upstream and downstream and accelerated on the flanks. Following Dols et al. (2008), we prescribe a radial slowing of the flow consistent with the ion temperature observed along the Galileo J0 (first) flyby. The ion temperature increases on the flanks because of the pickup of SO2+ ions in the local fast flow. The increased electron and SO2+ densities are carried along the flow while the electron temperature decreases because of the efficient cooling process provided by the molecular atmosphere. The SO2 electron-impact ionization and dissociation are located mainly on the upstream hemisphere because of the efficient electron cooling processes. The SO2 resonant charge-exchange rate (SO2 + SO2+ -> SO2+ + SO2) is larger on the flanks. In the wake of Io, along the Galileo J0 flyby, the flux tubes are emptied of the upstream S and O ions because of charge-exchange reactions with SO2, with SO2+ becoming the dominant ion (Figure 11).

In Figure 8 we show the volume-integrated rates of each plasma-SO2 process. These results are computed using a 3D MHD simulation of the plasma flow around Io and a SO2 atmosphere description presented in Dols et al. (2012) with an equatorial vertical column of 5.6 x 10^{16} cm^{-2}. The MHD flow allows for a better description of the slowing of the flow in Io’s atmosphere, which affects the reaction rates and the results are thus somewhat different in detail to the 2D simulations shown in Figure 7.

Figure 8 provides a reasonable estimate of the relative contribution of each process. The dominant SO2 loss process is the electron-impact dissociation, which ultimately provides slow atomic neutrals that feed an extended corona of S and O. We note that in fact the simulations are not fully self-consistent because the S and O corona are prescribed. We aim to take a more consistent approach in future studies. Another significant process is a cascade of resonant charge exchange reactions, which provides slow and fast SO2 molecules, depending on the local flow speed where the charge exchange reaction occurs. This cascade of charge exchange and dissociation reactions potentially feeds neutral clouds of S, O atoms and SO2 molecules similar to the observed Na structures (Figure 11), which extend along Io’s orbit and possibly through the whole magnetosphere (discussed in section 4).
Such modeling efforts require a consistent and robust set of observational constraints, mainly provided by Galileo instruments. The plasma measurements are essential to infer the plasma flow perturbation, the ion temperature, density and composition. Unfortunately, the Plasma Science (PLS) sensitivity evolved during the Galileo mission and PLS plasma densities are often not consistent with those inferred from the Plasma Wave Sensor (PWS) measurements (Dols et al. 2012). This lack of reliable plasma observations limits the reach of the numerical modeling of the local interaction at Io. The Galileo flybys were also relatively far from the denser part of the atmosphere (~200–900 km) and thus mostly constrain the tenuous corona. Moreover, no Galileo flybys were achieved in eclipse and on the nightside. Thus, the spatial and temporal variabilities of the plasma-atmosphere interaction remain poorly constrained. A new mission at Io is needed to provide further major breakthrough in our understanding of its local interaction.

3.2 Plasma-Europa interaction

Galileo made 9 flybys of Europa between 1996 and 2000 on the upstream hemisphere, the flanks and >3 R_{Eu} downstream. These flybys were far (~200-3500 km) from the deep part of the atmosphere and, unlike Io, no flybys were achieved above the poles.

The relative velocity of the upstream plasma in Europa’s reference frame is ~100 km/s (Bagenal et al. 2015) and the background magnetic field ~450 nT (Kivelson et al. 2004). The electron thermal population (T_{el} ~ 20 eV) is warmer than Io’s with a 5% non-thermal population at ~250 eV (Sittler & Strobel 1987; Bagenal et al. 2015). The gyroradius of the average thermal ion is ~6 km. The Europa interaction is similar to Io’s, but weaker (as described by \( \alpha \) in the introduction of section 3) because of a less dense upstream plasma (n_e ~ 160 cm^{-3}). The magnetic perturbation along the E4 flyby of ~50 nT is described by Kivelson et al. (1999). Saur et al. (1998) estimate that ~80% of the upstream plasma flow is diverted around the moon.

The most important Galileo discovery at Europa is the confirmation of the existence of an electrically conducting (salty) ocean under the icy crust, based on the magnetic perturbations measured along several flybys. Consequently, a major focus of analyzing and modeling the Galileo observations is the derivation of the induction signal to sound the conductivity and depth of the sub-ice ocean (Khurana et al. 1998, 2002; Kivelson et al. 1999, 2000; Zimmer et al. 2000; Schilling et al. 2004).

More recently, water plumes were discovered with the UV cameras onboard HST (Roth et al. 2014a,b; Sparks et al. 2016). Indirect evidence of the plume existence were inferred from Galileo magnetometer observations along the E26 flyby at low (~400km) altitude upstream of Europa (Blocker et al. 2016; Arnold et al. 2019) and along the E12 flyby (Jia et al. 2018), and from Galileo observations of Europa’s ionosphere (McGrath & Sparks 2017). These plumes are intermittent (Roth et al. 2014a,b, 2017a) but if they are to be sampled by future missions at Europa, they might provide direct information about the composition of the sub-surface ocean.

The morphology of Europa’s oxygen aurora is remarkably different from Io’s. It is comprehensively studied by Roth et al. (2016) using the Space Telescope Imaging Spectrograph (STIS) UV imager onboard HST (see Figures 4i,j). These emissions are not located along the equatorial flanks like Io, but mainly above the poles and they are almost systematically brighter on the polar hemisphere that faces the centrifugal equator. These polar emissions are reminiscent of similar observations of the auroral polar limb at Io, driven by the emptying of flux tube
electron energy above and below the moon as discussed previously for impact ionization. Contrary to Io, Europa’s atmosphere is not localized around the equator and the vertical column is much lower than Io’s. Two-fluid simulations (similar to Saur et al. 1998) of the auroral emissions were presented in McGrath et al. (2004). These simulations, based on specific assumptions about the atmosphere distribution, assume no magnetic field induction and Europa’s location in the center of the torus. The results show bright limb emissions all around Europa’s disk and do not seem to explain the morphology observed in Roth et al. (2016) who state: “A comparison of the Saur et al. (1998) simulation results with the first images of the aurora morphology on the trailing hemisphere taken by STIS reveals significant differences of the observed and simulated emission pattern (McGrath et al. 2004, Figure 19.10). In contrast to the rather symmetric global limb glow in the model results, the observed morphology appears asymmetric and irregular, (...) and the brightest emissions are often found on the disk rather than right at or near the limb. Moreover, the area near the tangent points of the magnetic field lines at the flanks of Europa is fainter than the magnetic poles (...). Such a decrease of aurora excitation in this area is not expected for the symmetric interaction scenario as assumed in the model of Saur et al. (1998)”. Roth et al. (2016) proposed that the inductive magnetic field in Europa’s ocean might perturb the flow around Europa and suppress the formation of equatorial auroral spots seen at Io but this hypothesis has yet to be tested with numerical simulations.

The various numerical simulations of the Europa plasma-atmosphere interaction are similar to Io’s: Two-fluid with electron and single ion species (O2+) in a constant uniform magnetic field (e.g., Saur et al. 1998), MHD (e.g., Schilling et al. 2007, 2008; Blocker et al. 2016), multi-fluid MHD (Liu et al. 2000; Rubin et al. 2015), hybrid (e.g., Lipatov et al. 2010) and multi-chemistry (e.g., Dols et al. 2016) with the goal of matching the Galileo plasma observations, understanding the main processes driving the interaction, constraining the global atmosphere (including plume sources), estimating the neutral loss rates and constraining the subsurface ocean. As the Galileo flybys did not probe the denser atmosphere, the simulations usually assume a large scale global O2 atmosphere with a scale-height ranging from 100-200 km and some upstream-downstream asymmetries due to the thermal sputtering source upstream.

Saur et al. (1998) focused on the plasma interaction and the formation of an O2 atmosphere. They inferred an equilibrium atmospheric column by balancing the sputtering sources and the atmospheric losses, constrained by the oxygen auroral emissions observed by HST. Using a relatively low upstream plasma density ~40 cm−3, they compute an equilibrium atmosphere with a vertical column of 5 x 10^{14} cm−2, a 145 km scale height and ~70 km exobase. The resulting atmospheric loss by ionization is estimated at ~6 kg s−1 and the atmospheric sputtering loss by charge exchange and elastic collisions above the exobase ~40 kg s−1.

Dols et al. (2016) focused on the multi-species chemistry, using a simplified 2D plasma flow described as an incompressible flow around a perfectly conducting body of radius 1.0 REu. Figures 9 and 11 show simulation results under a similar assumption of a perfectly conducting obstacle but we assume that the obstacle extends to 1.26 REu to provide results similar to Io’s shown on Figures 7 and 8. The assumed O2 atmosphere is spherically symmetrical, with a scale-height of 150 km and a vertical column of 5 x 10^{14} cm−2, consistent with observations. As Europa’s atmosphere is more tenuous than Io’s, the plasma variations close to the moon are smaller.

After comparing the general properties of the plasma variations around Europa, we now turn to the reaction rates integrated on the whole simulation volume. The Europa volume-
integrated rates for each plasma-O₂ process are presented in Figure 10 and should be understood as an illustration of the relative magnitude of each process. As for Io in Figure 8, we now use a MHD flow that is not completely diverted around the moon so that 20% of the flow reaches the surface (\(\alpha = 0.8\)), consistent with Saur et al. (1998). For these results, first reported here, we adopt this flow description to make the results comparable to Io’s.

Similar to the Io case, a cascade of resonant charge-exchange reactions is an important neutral loss process at Europa but, in general, all rates are much smaller than at Io. The H₂ chemistry is included in the simulations but the H₂ atmospheric loss rates due to plasma-neutral reactions in the atmosphere are insignificant. The escaping flux of H₂ (~2 x 10²⁷ s⁻¹) is probably lost by thermal escape after surface sputtering of the icy surface. H₂ is probably the source of the extended neutral cloud detected around Europa (see Section 4) as the O₂ rates calculated here (~0.5 x 10²⁷ s⁻¹) are likely not sufficient to feed a dense cloud of neutrals.

Blocker et al. (2016) use MHD simulations to study the effect of localized plumes on the global interaction. They show that each plume forms an Alfven winglet embedded in the main Alfven wing caused by the interaction with the global atmosphere. The plasma production or neutral loss resulting from the direct interaction at the plume is probably very small compared to the effect of the global atmosphere. Jia et al. (2018) and Arnold et al. (2019) used respectively 3D multi-fluid and hybrid plasma code to demonstrate the presence of plumes during some Galileo flybys (E12 and E26). They do not report the plasma or neutral production rate of their simulation but it should be noted that, in the numerical simulation community (both for Io and Europa), there is a lack of consensus on the description of the background atmosphere. Thus, it is usually difficult to compare the plume column density and plasma and neutral production inferred by the different authors.

### 3.3 Io-Europa Comparison

Properties of the plasma interactions with Io and with Europa are summarized in Table 3 while Figure 11 shows the plasma densities and ion composition downstream of the interactions with Io and Europa. In the Io case we did not include electron beams in this simulation so the cold, dense wake is missing. In each case the inflowing atomic ions are replaced downstream with molecular ions, and transition back to mainly atomic ions near ~2.0 R₉ and ~1.0 R₄Eₚ.

While our main conclusion is that the neutral loss at Europa is much smaller than at Io, for both Io and Europa, comprehensive self-consistent models of the full, coupled plasma/atmosphere/neutral cloud system are still needed. The atmospheric part of such models could be built on Saur et al. (1998)’s concept of source and sink balance. The atmospheric sources would include the detailed sputtering rates by thermal torus ions, pickup ions, hot ions, and maybe fast neutrals and hot electrons. The atmospheric loss processes would include the ionization, elastic collisions, charge-exchange and molecular recombination. These loss rates would be used as input to a neutral cloud model similar to Smith et al. (2019). Such a model could also assess the significance of Europa’s atmosphere as a neutral and plasma source for the Jovian magnetosphere.

A remarkable difference between the interactions at Io and Europa is the absence of parallel electron beams in the wake of Europa. It is thought that at the foot of Io’s Alfven wing, electrons are accelerated toward Jupiter to produce the footprint aurorae and also in the other direction to produce the parallel electron beams detected at Io (Bonfond et al. 2008). As footprint
auroras are sometimes detected at the foot of the Europa’s Alfven wing, it was expected that parallel electron beams would be present at Europa as well. Moreover, Io’s dense wake is thought to be caused by electron beams ionization in the downstream hemisphere and Galileo measurements in Europa’s wake did not reveal a dense plasma comparable to Io’s (Kurth et al. 2000; Paterson et al. 1999). One possible explanation of the non-detection of parallel electron beams along the Galileo flybys is that, because of Europa’s weaker interaction, the beams are located further downstream and so Galileo missed them. An alternative scenario is that the local interaction at Europa does not systematically produce footprint auroral emissions and concurrent electron beams.

In summary, the strong plasma-atmosphere interaction produces locally at Io only ~200 kg/s of ions but up to 2000 kg/s of neutral dissociation products are distributed around Io’s orbit. Meanwhile at Europa the interaction is much weaker. The interaction produces at best 20 kg/s of O$_2^+$ locally and is probably a minor source of plasma to the magnetosphere of Jupiter (yet comparable to Enceladus’s source rate of ions at Saturn). Nonetheless, extensive neutral clouds (probably hydrogen) have been detected along the orbit of Europa, as we discuss in the next section.

4 Neutral Clouds

While radio astronomers were still scratching their heads about Io triggering bursts of radio emission, in 1973 optical astronomers detected puzzling emission that were eventually interpreted as evidence of atmospheric escape from Io. Emissions from sodium and potassium were observed to emanate from a cloud around Io. Sodium is extremely efficient at scattering visible sunlight. Other neutral species are much harder to detect, particularly molecular species, so that our picture of the iogenic neutral clouds are largely based on the behavior of sodium and on models (Figures 12, 13). Table 4 lists the sources of neutrals and plasma at Io and Europa.

Models of neutral clouds take a flux of particles from the moon’s exobase (where atmospheric collisions become negligible) and follow the motions of the particles under the gravity first of the moon and then, farther away, Jupiter. The neutral particles interact with the surrounding plasma, being eventually ionized or charge exchanged. Photoionization also plays a role in lower density regions of the torus. Figure 13 shows a model recently published by Smith et al. (2019) that takes typical escape fluxes of different species at Io (Smyth & Marconi 2003) and Europa (Smyth & Marconi 2006), and a very simplified SO$_2$ escape flux from Io’s exobase and tracks particles under Jupiter’s gravity using a background plasma model to predict when along its trajectory a neutral particle of a particular species will be changed (via dissociation, ionization or charge exchange).

Figure 13 shows that molecular species are more easily dissociated and ionized, confining the molecular neutral clouds to the vicinity of the moons. Atoms with longer lifetimes (O, H) lead to atomic clouds that spread around the moon’s orbit. The color scale is the same for all five of the contour plots and shows that both Io and Europa neutral clouds are of remarkably comparable density. As shown in Figures 8 and 10, Io is a more prolific neutral source (~250-3000 kg/s) than Europa (~25-70 kg/s). The plasma near Io is denser and the neutrals are quickly removed, especially outside Io’s orbit.
4.1 Io Neutral Cloud

The first observational evidence of neutral atoms escaping Io was the detection of optical sodium D-line emission from a cloud in the vicinity of Io by Brown (1974). The efficient resonant scattering of sunlight by sodium produced the bright emission (Trafton et al. 1974; Bergstralh et al. 1975; Brown and Yung 1976). Many images of the sodium cloud have been acquired (see Figure 12 and reviews by Thomas et al. 2004; Schneider & Bagenal 2007). Voyager 1 observations revealed Io’s SO$_2$ atmosphere (Pearl et al. 1979) and a sulfur-dominated surface (Sagan 1979), indicating that Na was just a trace element in a neutral cloud dominated by sulfur and oxygen atoms and their compounds. While sodium is a trace component of the atmosphere (~few %), its large cross section for scattering visible sunlight makes it the most easily observed species in the neutral clouds (30 times brighter than potassium and orders of magnitude brighter than more abundant species’ emissions).

Early theoretical studies suggested that various neutral species could be removed from Io’s atmosphere by many different processes (with variable efficiency) to feed the neutral clouds: Jeans escape, charged particle sputtering of its surface, atmospheric sputtering, charge-exchange, direct single collisional ejection (Matson et al. 1974; Haff et al. 1981; Kumar 1982; Ip 1982; Johnson and Strobel 1982; Sieveka and Johnson 1984; McGrath and Johnson 1987; most completely compiled by Summers et al. 1989). More recently, electron impact molecular dissociation reactions are added to the list (Dols et al. 2008).

Models of the neutral clouds showed that electron impact ionization and charge exchange with torus plasma are significant loss processes on timescales of a few hours (e.g., Smyth and Combi 1988; Smyth 1992). Hence, the observed distributions of the neutral clouds are dependent upon both the neutral source and the spatial distribution of plasma properties in the torus. Sodium, potassium and sulfur have relatively short (2-5 hours) lifetimes against electron impact ionization in the densest regions of the torus. The rate coefficient for ionization of oxygen, however, is at least an order of magnitude lower than for sulfur so that charge-exchange loss of O with torus ions dominates over ionization. The minimum lifetime for O is around 20 hours (e.g., Thomas 1992) resulting in significant densities of neutrals farther from Io and an O neutral cloud that extends all the way around Jupiter.

After the initial detection by Brown (1981) of atomic oxygen emissions from Io’s neutral cloud at the wavelength of 630.0 nm leading to an estimate of a ~30 cm$^{-3}$ oxygen atoms, further observations of these optical emissions from the Io cloud by Thomas (1992) and close to Io by Oliversen et al. (2001) showed substantial variations with longitude, local time and Io phase. Meanwhile, atomic emissions were also detected in the UV. Atomic sulfur emissions at 142.9 nm and atomic oxygen emissions at 130.4 nm were observed with a rocket-borne telescope by Durrance et al. (1983). The first detections of neutral O and S were around 180° in Io phase away from Io itself and analyzed by Skinner and Durrance (1986) to infer densities of neutral O and S of 29 ± 16 cm$^{-3}$ and 6 ± 3 cm$^{-3}$ respectively.

The presence of dense neutral clouds along the orbit of Io is also confirmed by Lagg et al. (1998) who note losses of energetic sulfur and oxygen ions (~10s keV/nucleon) with a 90° pitch angle measured by the Galileo Energetic Particle Detector (EPD) instrument. These ions are thought to be removed by charge exchange with extended neutral clouds with a density ~35 cm$^{-3}$, consistent with previous estimates of Brown (1981) and Skinner and Durrance (1986).
The International Ultraviolet Explorer (IUE) satellite detected UV emissions from O and S near Io (Ballester et al. 1987). Using 30 observations by the HST-STIS, Wolven et al. (2001) mapped out O emission at 135.6 nm in the UV to 10 R\textsubscript{Io}. They also demonstrated that these neutral emissions downstream of Io were brighter than those upstream, that there seemed to be a weak, erratic System III longitude effect, and that the local time (dawn versus dusk) asymmetry depends on the Io phase angle.

The Hisaki UV observatory in Earth orbit has provided new oxygen observations, mapping out Io's neutral oxygen cloud to show it comprises a leading cloud inside Io's orbit and an azimuthally uniform region extending to 7.6 R\textsubscript{J} (Koga et al. 2018a,b, 2019). The peak number density of oxygen atoms is estimated at 80 cm\textsuperscript{-3}, spreading ~1.2 R\textsubscript{J} vertically. The Hisaki team estimate the source rate of oxygen ions at 410 kg/s, roughly consistent with previous studies (Smyth & Marconi 2003; Delamere and Bagenal 2003; Yoshioka et al. 2018). When Io exhibited a volcanic eruption in 2015, lasting ~90 days, Koga et al. (2019) used Hisaki observations of the time variations of O and O\textsuperscript{+} to show volcanism shortens the lifetime of O\textsuperscript{+} and that Io's neutral oxygen cloud spreads outward from Jupiter during the 2015 volcanic event. The number density of O in the neutral cloud at least doubles during the active period.

From 1977 to 2011 William H. Smyth and colleagues published ~25 papers applying a neutral cloud model to study satellite atmospheres and neutral clouds (Smyth & MacElroy 1977; Smyth et al. 2011). The Smyth neutral cloud model involved solving the kinetic equations for a population of neutral particles embedded in prescribed torus plasma. For each small time-step, the state (location, velocity, ionization state) of the different particle species is updated following the consequences of the effects of gravity and collisions (elastic, inelastic, and chemically reactive), which are calculated for the average conditions in each model bin. They applied their model, including various refinements, to study Io's Na, K, O, S, SO\textsubscript{2} and SO corona, plus the plasma torus properties (Smyth & Marconi 2003, 2005; Smyth et al. 2011). The recent Smith et al. (2019) model shown in Figure 13 is conceptually similar to the Smyth models, with updated reaction cross-sections, updated neutral fluxes from the exobase at Io and Europa and incorporating current data on the variability of conditions at the orbit of Io.

Detailed measurements of Io's sodium cloud require models to explain the main "banana-shaped" cloud, a "directional feature" or jet, as well as a "stream" of sodium ENAs (100 eV to keV) that spread out into a nebula extending for 100s of R\textsubscript{J} (Figure 12). The main sodium cloud is consistent with a roughly uniform corona of sodium atoms (a little above escape speed) around Io (Schneider et al. 1991a; Burger et al. 1999, 2001) producing a uniform source of an extended cloud that is shaped by interaction with the surrounding plasma (Smyth & Combi 1997). Jets of fast sodium neutrals require a process that includes acceleration, probably as an atomic or molecular ion, followed by a neutralizing charge exchange (or dissociative recombination) reaction that sends out a fast (~100 km/s) neutral or 1.2 keV ENA (Schneider et al. 1991b; Wilson & Schneider 1994; 1999). We return to the extended sodium nebula in section 6.

The main goal of Smith et al. (2019) was to show that Io's neutral material, whatever its composition, would not significantly reach Europa’s orbit. The Smith et al. (2019) model illustrated in Figure 13 assumes that only SO\textsubscript{2} escapes directly from Io with a canonical rate of 1 ton/s and a prescribed low velocity distribution. They produce iogenic neutral clouds that are consistent with observations of O and S emissions (Skinner & Durrance 1986; Koga et al. 2018a). But there are no observations of the neutral SO\textsubscript{2} cloud around Io. Future models of the
neutral clouds need to include sources of SO₂, S and O based on quantitative results from models of the plasma-atmosphere interaction (section 3.1)

Smyth and Marconi (2003) and Smith et al. (2019) study the formation of extended neutral structures but to this day, a self-consistent approach of their formation, from the processes in the atmosphere of Io, to the neutral cloud and finally to the torus ion supply, has not yet been carried out. Such extended neutral structures of S, O and SO₂ are notably difficult to observe (Brown & Ip 1981; Durrance et al. 1983; Koga et al. 2018a,b), beyond the minor Na species and we hope that in a near future, new creative observational methods will help to constrain quantitatively these extended neutral structures and improve our understanding of their atmospheric sources.

4.2 Europa Neutral Cloud

Strong indications of an extended source of neutrals escaping from Europa were implied by measurements of (a) depletion of energetic protons at about the orbital distance of Europa (Lagg et al. 2003; Kollmann et al. 2016), and (b) energetic neutral atoms (vENAs: 10s keV per nucleon) observed by the MIMI instrument on Cassini as it flew past Jupiter (Mauk et al. 2003, 2004). A stringent limit of ~8 cm⁻³ on the density of atomic oxygen from Cassini UVIS measurements (Hansen et al. 2005) meant that the neutral cloud, estimated to have a density of 20-50 cm⁻³ to produce the observed vENAs, must be mostly hydrogen (atomic or molecular) rather than oxygen (consistent with simulations of Shematovich et al. 2005; Smyth & Marconi 2006; Smith et al. 2019). The fate of the vENAs is discussed in section 6.

The low mass of hydrogen allows it to easily escape Europa so that hydrogen has a much higher (at least x10) escape rate than oxygen. Roth et al. (2017a) detected an extended corona of atomic H around Europa, consistent with electron impact dissociation of molecular H₂, as modeled by Smyth & Marconi (2006), but the net contribution of escaping atomic H is relatively minor (~5%). The Smith et al. (2019) model is similar to Smyth & Marconi (2006) but applies additional particle interaction processes, updated reaction cross-sections and updated neutral fluxes from the exobase. The Europa neutral clouds are presented on the right side of Figure 13, showing that the dominant species is H₂ that extends all the way around Europa’s orbit with oxygen (particularly in molecular form) being more limited to the Europa environment. Smith et al. (2019) also conclude “Source rate changes take longer to impact the Europa neutral cloud than the Io neutral cloud. The dominant processes at Europa’s orbit have lifetimes from at least 2–3 days up to longer than a week, while at Io, the neutral particles start interacting (with the plasma) in 8–13 hr. Additionally, the range in observable ambient plasma environments can vary particle interaction rates by more than an order of magnitude.”

Recently, Nenon & Andre (2019) note the removal of energetic (~MeV) sulfur ions with ~90° pitch angle near Europa’s magnetic flux-shell. Based on the relative cross sections at these energies and an estimate of the neutral clouds densities (Smith et al. 2019), they argue that inward-transported energetic sulfur ions interact mainly with the extended hydrogen cloud while protons interact mainly with the tenuous, more equatorially-confined oxygen cloud. When protons charge-exchange with Europa’s neutral hydrogen and oxygen clouds, they are lost as vENAs – as detected by the Cassini MIMI instrument (Krimigis et al. 2002; Mauk et al. 2004). Nenon & Andre (2019) point out that since the heavy energetic ions tend to be higher ionization states (Clark et al. 2016), their interaction with Europa’s neutral clouds reduces their charge state so that when they move inward to Io’s neutral cloud they are singly charged (Mauk et al. 2004).
After charge-exchanging with Io’s neutral clouds, the heavy neutrals might leave the system as vENAs although such heavy vENAs have not yet been observed. The estimates of the Europa neutral cloud density of Mauk et al. (2004) and the conjecture of Nenon & Andre (2019) on the neutral clouds composition and extent are based on first order calculations and ultimately will be tested by the Jovian Energetic Neutral and Ions instrument onboard the ESA JUICE mission to Jupiter.

Neutral clouds of sodium (Brown & Hill 1996) and potassium (Brown 2001) have also been detected around Europa. Burger & Johnson (2004) model the distribution of sodium and found a cloud shape similar to the O cloud of Smith et al. (2019) in Figure 13, extending farther on the trailing (upstream) side where particles are moving away from Jupiter into lower plasma densities compared with the leading (downstream) side where particles are moving towards Jupiter into higher plasma densities. The big question has been whether Europa’s alkalis are representative of its brines and ocean salinity (endogenic) or is this merely iogenic material painted onto Europa’s surface (exogenic). A recent review by Johnson et al. (2019) summarizes the current situation as follows: “Recent ground-based observations of Europa point towards the presence of endogenic materials (possibly chlorinated salts) on the surface (Brown and Hand 2013; Fischer et al. 2015, 2016; Ligier et al. 2016), and irradiation experiments by Hand and Carlson (2015) suggest that NaCl-rich material from the sub-surface ocean may explain Europa’s yellow-brownish color at visible wavelengths. In addition, the ambient sodium and potassium emissions observed (Brown and Hill 1996; Brown 2001) also suggest that there is coupling between the surface and the likely ‘salty’ ocean (e.g., Johnson 2000; Leblanc et al. 2002, 2005).” Recent data from Juno’s JIRAM instrument is providing further information on Europa’s surface composition, ice structure and temperature (Filacchione et al. 2019).

5 Plasma Torus

The Io plasma torus comprises three main regions: (1) the outer region that has a roughly circular cross-section – sometimes called the “doughnut” – that contains 90% of the mass and emits most of the UV emission; (2) just inside Io’s orbit there is narrow but vertically-extended region – sometimes called the “ribbon” – that is bright in UV and particularly visible wavelengths; and (3) extending inwards from the ribbon is a thin disk or “washer” that emits visible (but no UV) light. Figure 14 illustrates these three regions and their properties are listed in Table 5. The warm torus extends past the orbit of Europa (section 5.4) and merges into the plasma sheet.

Optical emissions from a toroidal cloud of $\text{S}^+$ ions surrounding the orbit of Io were first detected in ground-based observations by Kupo et al. (1976), which Brown (1976) recognized as coming from a cold, dense plasma. The Voyager 1 flyby of Jupiter in 1979 revealed Io spewing out $\text{SO}_2$ from active volcanoes and provided detailed measurements of the Io plasma torus both from the strong emissions in the EUV, observed remotely by the Voyager Ultraviolet Spectrometer (UVS) (Broadfoot et al. 1979), as well as in situ measurements made by the Plasma Science (PLS) instrument (Bridge et al. 1979) and the Planetary Radio Astronomy (PRA) instrument (Warwick et al. 1979).

Since Voyager, the Io plasma torus has been observed remotely via visible and UV emissions as (Thomas 1992; Hall et al. 1994; Gladstone et al. 1998; Feldman et al. 2001; 2004) well as in situ by the Galileo spacecraft (Gurnett et al. 1996, 2001; Frank & Paterson 2000). Each of these techniques for measuring the plasma properties in the torus has its pros and cons.
The remote sensing techniques provide good temporal and spatial coverage but suffer from being integral measurements along the line of sight as well as being dependent on calibration of the instrument and accurate atomic data for interpretation of the spectra. Moreover, a very broad wavelength range is needed to cover emissions from all the main ion species. The in situ plasma measurements provide detailed velocity distributions but suffer from limited spatial and temporal coverage as well as poor determination of parameters for individual ionic species in the warm region of the torus where the spectral peaks for different species overlap. Since these two data sets are complementary, they can be combined to construct a description of the plasma conditions in the torus, i.e. an empirical model, that can be compared to theoretical models based on the physical chemistry of the torus plasma (e.g. Bagenal 1994; Herbert & Hall 1998; Herbert et al. 2003, 2008; Smyth & Marconi 2005; Smyth et al. 2011; Nerney et al. 2020). A summary of observations and theoretical understanding at end of Galileo mission is provided by Thomas et al. (2004).

The dominance of sulfur and oxygen composition of heavy ions throughout the magnetosphere tell us that these products of volcanic gases fill the vast volume of Jupiter’s magnetosphere. At the same time, energetic particles from the outer magnetosphere are transported inwards, bringing in supra-thermal ions that charge-exchange with the neutral clouds, plus electrons that ionize and excite UV emissions. In the next sections we first describe the underlying physical processes in the Io-Europa space environment and then summarize current understanding of the three torus regions.

5.1 Physical Processes

The key physical processes controlling the plasma in the Io-Europa environment are ion pick-up, centrifugal confinement to the equatorial region, radial transport and collisional processes (dissociation, ionization, charge-exchange, radiation, etc; gathered under the term “physical chemistry”) that drive the radial distribution of different ion species as well as the energy of the plasma.

**Ion Pick-Up:** As discussed in Section 3 above, a relatively small amount of plasma is directly produced in the interaction with either Io’s or Europa’s atmospheres. Most of the plasma is produced via electron impact ionization of the extended neutral clouds (Section 4 above) where the neutral atoms that follow Keplerian orbits (~17 and 14 km s^-1 at Io and Europa respectively) around Jupiter. The plasma is coupled via Jupiter’s magnetic field to the planet’s electrically-conducting ionosphere, which corotates with the planet’s ~10 hour spin period (~75 and 118 km s^-1 at Io and Europa respectively). Minor deviations from rigid corotation mean that typical plasma flow speeds are ~5% less than corotation at Io (71 km s^-1) and ~15% sub-corporotational at Europa (~100 km s^-1). When a slowly moving atom is ionized (either via electron impact or charge exchange), the fresh ion starts with an initially high velocity relative to the corotating plasma (55 and 85 km s^-1 at Io and Europa respectively). Each pickup ion therefore experiences an electric field due to its motion relative to the local magnetic field (and the plasma) and is accelerated – i.e. "picked up" – gaining a gyro-velocity (in the plane perpendicular to the local magnetic field) equal to its initial motion relative to the corotating plasma. Each fresh ion gains a gyro-energy dependent on its mass: 270 eV for O^+, 540 eV for S^+ and 1.1 keV for SO_2^+ at Io's orbital distance; 650 eV for O^+ and 1.3 keV for O_2^+ at Europa’s orbital distance. Fresh O^+ pick-up ions gyrate around the magnetic field at ~2 and 0.5 Hz with a 5- and 40-km gyro-radius at Io and Europa respectively. The energy of these fresh ions
ultimately comes from Jupiter’s rotation, coupled to the plasma via the magnetic field. If the gyro-speed were distributed into an isotropic Maxwellian distribution (e.g., via Coulomb collisions) the O+ and S+ ions would have temperatures of 2/3 their initial pick-up energy. The corresponding pick-up electrons gain negligible gyro-energy but are accelerated to corotate with the surrounding plasma. Electrons are heated quite quickly via Coulomb collisions with the ions but only in the inner torus does the plasma hang around long enough to get close to full thermal equilibrium. Evidence of local pick-up comes from the EMIC waves observed far downstream of Io at the SO2+ and SO+ ion gyro-frequencies (Warnecke et al. 1997; Russell & Kivelson 2000; 2001). These waves are generated by the unstable “ring-beam” velocity distributions of fresh pick-up ions. The presence of a background population of thermalized ions suppresses the generation of EMIC waves which explains why emissions are not detected at the gyro-frequencies of the dominant ion species such as S+ and O+ (Crary & Bagenal 2000).

When a neutral particle is ionized it not only picks up gyro-motion but it also starts to drift (from $\mathbf{E} \times \mathbf{B}$) at the bulk velocity of the flowing plasma. Ions are added to the Io torus at a rate of about 1 ton/s, which corresponds to $\sim 10^{-3}$ ions cm$^{-3}$ s$^{-1}$ or just $\sim 5$ ions cm$^{-3}$ per 10-hour Jupiter spin period. When integrated around Io’s orbit, the additional radial current to pick up these fresh ions and accelerate them to corotation is 0.6 megaAmp (for a torus height of 2 RJ). The electrical currents close along the magnetic field, coupling the plasma to the planet’s ionosphere (that is collisionally coupled to the neutral atmosphere). The corotating torus plasma continually experiences an inward $\mathbf{J} \times \mathbf{B}$ force associated with an azimuthal current through the torus (see derivations in Cravens (1997) chapter 8). This corotation current is about 10 megaAmp (for a $\sim 2\times 2 = 4$ RJ$^2$ torus cross-section). On the other hand, keeping the plasma corotating as it moves into the plasma sheet (as well as balancing pressure gradient forces) drives radial currents in the plasma sheet of several 10s megaAmps, closing via parallel current from/to the ionosphere (Cowley & Bunce 2001; Nichols et al. 2015).

**Centrifugal confinement.** Torus plasma trapped by Jupiter’s magnetic field is confined toward the equator by centrifugal forces. A corotating ion gyrates around local field lines several times per second while bouncing along field lines every few hours. On field lines at Io's orbit, each ion experiences about 1 g of centrifugal acceleration outward from the rotation axis. Ions in a Maxwellian velocity distribution are distributed along the magnetic field line, 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, $\sim 10^\circ$ from the rotation axis, the centrifugal equator has 2/3 of the tilt, or $\sim 7^\circ$ from Jupiter’s rotational equator (Hill et al. 1974). As the tilted torus corotates with Jupiter, the torus viewed from Earth appears to wobble $\pm 7^\circ$. Non-dipolar components to the field can measurably warp the centrifugal equator.

In equilibrium, one can consider the plasma distribution along the field as a fluid in balance between the effect of gradients in the thermal pressure of the plasma ($nkT$) and the centrifugal force, much as the vertical distribution of a planet’s atmosphere comes from a balance between pressure gradient and gravitational forces. Thus, the torus vertical structure is a rough indication of ion temperature. The fluid approach can incorporate further complexity associated with the ambipolar electric field ($\sim 15$ volts across the torus) arising from small charge separation between ions (more strongly affected by the centrifugal force) and the much lighter electrons, plus the addition of multiple ion species and thermal anisotropy.
For the approximation of a single, isotropic ion species, cold electrons (with net charge neutrality) and a roughly dipole magnetic field, the north-south or vertical dimension (z-axis) distribution of plasma density \( n(z) \) about the centrifugal equator is a Gaussian function

\[
n(z) = n(z=0) \exp\left(-\frac{z}{H}\right)^2
\]

where the scale height \( H \) is determined by the spin rate of Jupiter, \( \Omega \), the ion temperature, \( T \), and the mass of the ions, \( A \):

\[
H = \left[\frac{2}{3} \frac{kT}{m_p A \Omega^2}\right]^{1/2} = H_o \left[\frac{T(eV)}{A(amu)}\right]^{1/2}
\]

For \( H \) in units of Jovian radii, \( R_J \), \( T \) is in eV and \( A \) is average ion mass in atomic mass units, we have \( H_o = 0.64 R_J \). For a more detailed description of the “diffusive equilibrium” distribution of plasma along the magnetic field for a multi-species, anisotropic plasma see Bagenal (1994) or Dougherty et al. (2017). To include a non-thermal (non-Maxwellian) tail to the particle velocity distribution see Moncuquet et al. (2002).

**Radial Transport:** Sulfur and oxygen ions, assumed to originate in the Io plasma torus, are detected throughout the magnetosphere, implying that plasma from the Io plasma torus is spread throughout the magnetosphere. For a region of a planetary magnetosphere where the plasma is tightly coupled to the planet (called a “plasmaphere”) and where rotational effects are small (e.g. Earth), radial transport of plasma has been described as a diffusive process whereby neighboring fluxtubes randomly switch positions. For the Earth, such fluxtube interchange was assumed to be driven by turbulent motions in the ionosphere (Falthammer 1966; Brice 1968). The transport of plasma in a rotation-dominated magnetosphere such as Jupiter’s, is usually described to be via centrifugally-driven flux tube interchange (e.g., Hill et al. 1981). The interchange instability is the magnetospheric analog of the Rayleigh-Taylor instability, the same instability that drives convection in a planetary atmosphere or a pot of boiling water. The effective gravity, dominated by the centrifugal force of corotation, is radially outward. The essence of the centrifugally-driven interchange instability is that heavily-loaded magnetic flux tubes from the source region move outward and are replaced by flux tubes containing less mass (the outer magnetosphere is relatively empty) moving inward, thereby reducing the (centrifugal) potential energy of the overall mass distribution without significantly altering the configuration of the confining magnetic field. And because Jupiter's magnetosphere is a giant centrifuge, outward transport is energetically strongly favored over inward transport.

In the standard theory, interchange rate is regulated by the electrical conductivity in Jupiter's ionosphere, at the “feet” of the magnetic flux tubes (Hill 1979). Early studies used *Voyager* measurements of the onset of deviation from corotation (McNutt et al. 1981) to constrain the value of ionospheric conductance (Hill 1980; Hill et al. 1981). But theoretical models using only ionospheric conductance to limit fluxtube interchange have difficulty in matching the long lifetimes (~20-80 days) for plasma in the Io torus derived from physical chemistry models (discussed in the next section). A detailed discussion of possible additional mechanisms (e.g., ring current impoundment, velocity shears, etc.) to slow down radial transport from the torus is given in section 23.7 of Thomas et al. (2004). While many have looked, direct evidence of the instability has been very rare (Thorne et al. 1997; Bolton et al. 1997; Kivelson et al. 1997; Frank and Paterson 2000; Russell et al. 2005). The theoretical problem turns out to be less an issue of explaining why outward transport occurs, but more a matter of explaining why it occurs so slowly. Or, put another way, why is the torus so long-lived, and therefore so massive?
An empirical approach describes fluxtube interchange as a diffusive process that depends on the radial gradient of the content of a magnetic flux tube, \( NL^2 \) where \( N \) is the number density integrated over an L-shell of (dipolar) magnetic flux (Richardson et al. 1980). A diffusion coefficient (usually simplified as a constant times a radial power-law) is derived to match observed radial profiles of fluxtube content. The strong preference for outward transport via centrifugally-driven fluxtube interchange means that the derived diffusion rates are about a factor of 50 faster for transport outwards from the source at Io than inwards. This is a major factor explaining why there is \( \sim 100 \) less mass in the inner torus (Richardson et al. 1980, 1981; Bagenal 1985; Herbert et al. 2008).

One topic that theorists struggle with understanding is the scale on which centrifugally driven interchange is being driven. Richardson and McNutt (1987) looked at the currents into the \textit{Voyager} PLS sensors at the highest temporal resolution (L modes) and found that on 0.24 second timescale (which translates to an effective spatial resolution of \( \sim 20 \) km), the plasma density does not fluctuate more than 20% (more typically <5%). These observations ruled out theories such as proposed by Pontius et al. (1986) that required interchange of full and (essentially) empty flux tubes. In a survey of \textit{Galileo} data, Russell et al. (2005) showed that small-scale (\( \sim 2 \) second duration, corresponding to scales of 100-1000 km) magnetic perturbations indicative of inward-moving fluxtubes (relatively empty of dense, cold plasma but could have plenty of energetic particles) occurred rarely (\( \sim 0.32\% \) of the time). This suggests these fluxtubes need to move in quite rapidly (10s km/s) compared with the slow outward motion of full fluxtubes. Hess et al. (2011a) argues that the fast, inward-moving, empty fluxtubes are analogous to the Io Alfven wing. The Alfven waves propagating along the fluxtube are responsible for acceleration of electrons close to the ionospheres of Jupiter. Some of the electrons are trapped between the mirror points of the flux tube and form the supra-thermal electron population observed by Frank & Paterson (2000) and required by physical chemistry models (described in the next section).

The inward-moving fluxtubes containing energetic particles are often called “injections”. Such injections of energetic particles have been observed in the Io-Europa environment (Mauk et al. 1999; Haggerty et al. 2019) and are clearly a major element in radial transport within these regions. The structures are much broader in scale than the events observed in magnetometer data by Russell et al. (2005) and their dispersion in energy suggests such structures have aged (presumably as they travelled inwards). Isolated auroral features equatorward of the main auroral oval were first observed with HST and have been associated with injection of hot electrons resulting from flux tube interchange (Mauk et al. 2002; Krupp et al. 2004; Grodent 2015; Dumont et al. 2014, 2018). Dumont et al. (2014) suggest that such injections seem to be quite common (one per 24 hours), appear at all SIII longitudes, peak close to Europa’s orbit but sometimes spread to a radial distance \( \sim 7 \) RJ and even to Io’s orbit (Bonfond et al. 2012). But so far, only a single clear injection event has been reported (Mauk et al. 2002) where observations of an electron injection observed in situ by \textit{Galileo} are concurrent with an auroral equatorial protrusion observed by the Hubble Space Telescope. It remains unclear, however, what the physical relationship is between injections (either the small scale empty magnetic fluxtubes occasionally observed in magnetometer data or the larger scale dispersed energetic particle structures) and radial transport processes such as fluxtube interchange.

Whole fluxtubes possibly interchange in the inner magnetosphere where the field is dipolar. But as plasma moves beyond Europa’s orbit, and as the plasma is hotter at larger distances, the plasma pressure begins to dominate over the magnetic field and one expects that
other more local instabilities likely dominate radial transport (Vasyliunas 1983; Krupp et al. 2004; Kivelson & Southward 2005). The topic of radial transport and energization of plasma populations is a major active topic that is being addressed by a combination of auroral emissions (from HST and Juno) and in situ particles and fields observations by the Juno mission.

**Physical Chemistry.** In the bulk of the Io-Europa space environment the transport times are relatively long (~1 to several months) so that substantial plasma densities accumulate (1000-3000 cm\(^{-3}\)) and collisions are relatively frequent (hours to days). This means that collisional reactions (excitation, ionization, dissociation, charge-exchange) are important sources and losses of both particles and energy. For each species the source and loss terms are different and depend on properties (neutral and plasma density, temperature, etc.) that can vary in space and time, so one needs to solve a self-consistent system including both physical chemistry and diffusive transport. Early models took a homogeneous box with an input of neutrals with specified composition (e.g. 1 ton/s of O and S neutral atoms in the ratio 2:1 consistent with dissociation of SO\(_2\)) and a specified timescale for transport out of the box (e.g. 40 days). Some initial plasma is included, reaction rates specified, and the system evolved to equilibrium. It was quickly realized that an additional source of relatively hot electrons needs to be added to the system in order to sustain the system (Shemansky 1988; Barbosa 1994).

A major difficulty in building such models, particularly in early studies, is the fact that the atomic data for many of the various reactions are not agreed upon or even known. McGrath & Johnson (1989) calculated critical charge exchange reaction rates for typical torus conditions. Taylor et al. (1995) developed the Colorado Io Torus Emission Package (CITEP) that took atomic data provided by Don Shemansky and the Bagenal (1994) torus model to predict emissions for various species at different wavelengths and viewing geometries. In 1997 a group of UV astronomers put together a database of UV emissions in the CHIANTI database (Dere et al. 1997). This public database has been updated periodically, the most recent being CHIANTI 8.0 (Del Zanna et al. 2013; Del Zanna & Badnell 2016). For example, Nerney et al. (2017) illustrates the effects of using different data bases on the analysis of UV observations obtained by Voyager, Galileo and Cassini to derive ion composition in the Io plasma torus, finding up to 40% changes in the derived abundances of some of the species between CHIANTI versions 4 and 8.

Such physical chemistry models of the Io plasma torus have been extended from a “cubic centimeter” in the center of the torus (Shemansky 1988; Lichtenburg et al. 2001; Delamere & Bagenal 2003) to radial profiles (Barbosa 1994; Delamere et al. 2005; Nerney et al. 2017; Yoshioka et al. 2014, 2017) and azimuthal variations (Steffl et al. 2008; Copper et al. 2016; Tsuchiya et al. 2019) as well as temporal variations apparently driven by volcanic outbursts on Io (Delamere et al. 2004; Kimura et al. 2018; Yoshioka et al. 2018; Tsuchiya et al. 2018). Delamere et al. (2005) considered the effect of an additional neutral source at Europa on the torus chemistry and found that the faster radial transport rate (\(V_r\) increasing from ~100 m/s at Io to few km/s at Europa) meant that the contribution was minimal. We return to the impact of Europa on the torus in Section 5.4.

Finally, it must be noted that the physical chemistry models of the torus assume sources of atomic O and S and do not yet include molecular species (e.g. SO\(_2\), SO, O\(_2\)) either as neutrals or ions and assume such molecules are quickly dissociated. While this is probably a reasonable assumption for most of the main, warm, outer torus, molecules probably play an important role in the ribbon and cold, inner torus (see section 5.3).
5.2 Warm Io Plasma Torus

The evolution of thinking about the Io plasma torus through the Voyager era illustrates the disconnect between the fields of astronomy and space physics. Initially, the two groups did not understand the other’s nomenclature. Pre-Voyager, the planetary astronomers talked of emissions from SII excited by electrons with temperatures of $\log_{10} T_e = 4.4 \pm 0.6$ K and densities of $\log_{10} [n_e] = 3.5 \pm 0.6$ cm$^{-3}$ (Brown 1976). Meanwhile, the Pioneer space physicists talked about in situ measurements of 100 eV protons with densities of 50–100 cm$^{-3}$ (Frank et al. 1976). As Voyager approached Jupiter, the UVS team said they were seeing surprisingly intense emissions from high densities of sulfur and oxygen ions. The Voyager PLS team scaled down their instrument sensitivities accordingly. A couple days later, Voyager 1 flew through the middle of the torus and measuring peak densities up to 3200 cm$^{-3}$ (Bridge et al. 1979; Warwick et al. 1979) with PLS only saturated in one high resolution spectrum.

The doughnut-shaped main warm torus outside Io’s orbit dominates the mass and energy of the system (Table 5). The plasma is warm (ion temperature ~60-100 eV) with a vertical scale height of ~1.0-1.5 RJ. The plasma moves slowly outwards, the electron density dropping from ~2000-3000 cm$^{-3}$ at Io’s 6 RJ orbit to 100-200 cm$^{-3}$ by Europa’s 9.4 RJ orbit (Figure 15), which it reaches in ~30-80 days (Bagenal et al. 2016; 2017). While there are small blobs of cool (~20 eV) plasma in the plasma sheet (~10-30 RJ, Dougherty et al. 2017) the bulk of the plasma rises from ~60-100 eV at Io to ~few 100 eV by Europa (Bagenal et al. 2015).

As the plasma expands radially outwards in fluxtubes of increasingly weaker magnetic field, one would expect the plasma to cool. But instead of cooling on expansion, the iogenic plasma is in fact clearly heated (by an as-yet-unknown process), as it moves outwards, reaching keV temperatures in the plasma sheet on timescales of weeks, requiring something like ~0.3-1.5 TW of additional energy input (Bagenal & Delamere 2011).

**Composition.** Despite multiple ways of observing the torus, no observation uniquely determines all 5 of the dominant ion species (O$^+$, O$^{++}$, S$^+$, S$^{++}$, S$^{+++}$) in the main Io torus region. The Voyager PLS instrument obtained excellent compositional measurements in the cold inner torus (<5.6 RJ) and in several cold blobs in the plasma sheet (Dougherty et al. 2017). But the analysis of both Voyager and Galileo data to obtain density, temperature and flow in the warm torus (Bagenal et al. 2015; 2016; 2017) required making assumptions about composition derived from a combination of UV emissions and physical chemistry models.

Bodisch et al. (2017) reports on minor ions detected in the torus and plasma sheet from the re-analysis of Voyager PLS data. They found protons comprise 1–20% of the plasma between 5 and 30 RJ (nominally ~10% in the torus) with variable temperatures ranging by a factor of 10 warmer or colder than the heavy ions. These protons, measured deep inside the magnetosphere, are consistent with a source from the ionosphere (rather than the solar wind) of $\sim 1.5–7.5 \times 10^{27}$ protons s$^{-1}$ (2.5–13 kg/s). Sodium ions are detected between 5 and 40 RJ at an abundance of a few percent (occasionally as much as 10%) produced by the ionization of the extended iogenic neutral cloud discussed in Section 4 above. Sodium ions have also been detected spectroscopically in the UV by Hall et al. (1994). Perhaps not surprisingly (given the expectation that the iogenic source of sodium is NaCl), chorine ions are also detected (at ~1% levels) in visible (Kuppers & Schneider 2000) and UV (Feldman et al. 2001) emissions. Feldman et al. (2004) also detected minor amounts of carbon ions and found no evidence of nitrogen, silicon or phosphorus ions.
Early discussions about the torus ion composition derived from UV emissions were plagued with poor knowledge of excitation and reaction rates, as well as debates about the role of hot electrons. The ionization state of the ions seems to increase with distance and the total emitted power (~1.5 TW) required an additional source of hot (say ~50–100 eV) electrons (Moreno et al. 1985; Smith & Strobel 1985; Smith et al. 1988; Shemansky 1988; Barbosa 1994). The Bagenal et al. (1992) study of torus composition combined analysis of in situ PLS data with *Voyager* UVS data analyzed by Shemansky (1987, 1988). This combined composition analysis became the basis of an empirical description of the Io plasma torus by Bagenal (1994), which was used to constrain early physical chemistry models of the torus (Schreier et al. 1998; Lichtenberg et al. 2001; Delamere & Bagenal 2003). The torus composition derived from *Voyager* 1 UVS emissions by Shemansky (1987) was strongly dominated by O\(^+\) ions (~40% of \(n_e\)), which required neutral input to the physical chemistry model of Delamere & Bagenal (2003) with O/S~4, about twice what one would expect from the dissociation of SO\(_2\).

The *Cassini* spacecraft flyby of Jupiter (with a primary goal of gaining a gravity assist to Saturn) provided an excellent opportunity to study UV emissions from the Io plasma torus between October 2000 and March 2001 (Steffl et al. 2004a,b). Spectral analysis of the torus emissions suggested the ion composition was very different at the *Cassini* epoch than that derived by Shemansky (1987) at the time of *Voyager* (bottom of Figure 15). Specifically, the abundance of O\(^+\) was reduced to 26% of \(n_e\), which Delamere & Bagenal (2003) could model with a neutral source of O/S~2, compatible with an SO\(_2\) origin.

Meanwhile, Delamere et al. (2005) expanded their physical chemistry model to 2 dimensions, assuming azimuthal symmetry. They averaged reactions over latitude and calculated radial variations in plasma properties for a fluxtube of plasma that was slowly moving outwards via centrifugally-driven fluxtube interchange. Note that the bounce periods for electrons and ions trapped in Jupiter’s magnetic field and the collisional reaction rates are relatively short compared with the transport timescale of 30-80 days. Beyond ~8 R\(_J\) the densities have dropped and the radial transport sped up so that the reactions and radiation have effectively ceased, “freezing in” the composition. The production of neutrals needed by Delamere et al. (2005) to match the *Cassini* UVIS data was comparable to the Smyth & Marconi (2003) neutral cloud model at Io (~7 x 10\(^{26}\) atoms/s) but required a steeper radial gradient.

Recent re-analysis by Nerney et al. (2017) of the *Voyager* 1 UVS data using the current atomic data for emission rates suggests an ion composition more consistent with the UV emissions observed in the *Cassini* era and with models of the torus physical chemistry matched to the *Cassini* UV data by Delamere et al. (2005) as shown in Figure 15. Nerney et al. (2017) also looked at the *Galileo* UVS data (June 1996), which actually showed a depletion of O\(^+\) emission compared with *Cassini*. Intriguingly, Herbert et al. (2001) also reported a decrease in O\(^+\) emission observed by EUVE at about the same time. We return to the topic of temporal variations in the torus below.

A measurement from the *Juno* mission that has important implications for the torus is the ability of the JADE instrument (McComas et al. 2017) to separate the O\(^+\) and S\(^{++}\) ion species that have the same mass/charge ratio (M/Q=16) with the *Juno*-JADE time-of-flight detector. Kim et al. (2019) report outside the torus (at 36 R\(_J\)) a ratio of O\(^+\)/S\(^{++}\) ion abundances varies from 0.2 to 0.7 (mean of 0.37 ± 0.12) and O\(^{++}\) to S\(^{++}\) ranges from 0.2 to 0.6 (mean of 0.41 ± 0.09). This is a bit lower than typical values of derived from UV spectroscopy and physical chemistry models (e.g. Delamere et al. 2005 found 0.95 to 1.4 at 9 R\(_J\)). Note that the *Juno* in situ measurements
extend up to 10s keV energies and the composition may reflect species-dependent heating between the torus and the plasma sheet. Later orbits will bring Juno into the plasma torus and test whether these composition trends persist.

JAXA’s Hisaki satellite has been in orbit around Earth since September 2013 (Yoshikawa et al. 2014). The UV spectrometer has been observing emissions (including new emission lines identified by Hikida et al. 2018) from the Io plasma torus, determining a background torus composition that is very similar to the post-Io-eruption Cassini epoch (Yoshioka et al. 2014, 2017). The greatest value of the Hisaki mission has been in monitoring spatial and temporal variations over several seasons, including a couple of periods of enhanced volcanic activity that we discuss below, after summarizing the main torus physical chemistry.

**Flow of Mass & Energy.** Summing up the mass in the Io plasma torus comes to total of \(~2\) megaton. A source of \(~1\) ton/s would replenish this mass in \(~40\) days. To get the total thermal energy of the torus, we multiply this total mass by a typical energy \((T_i \approx 60\ eV, T_e \approx 5\ eV)\) to obtain \(~6 \times 10^{17}\ J\). The torus emits (via more than 50 ion spectral lines, mostly in the EUV) a net power of \(~1.5\) TW. This emission is excited by electrons which, at a rate of \(~1.5\) TW, would drain all their energy in \(~7\) hours. While pickup supplies energy to the ions, which is fed to the electrons via Coulomb collisions, the pickup energy is not sufficient to maintain the observed emissions. An additional source of energy, perhaps mediated via plasma waves and/or Birkeland currents, is needed to heat the electrons.

Figure 16 shows the flow of mass and energy through the torus system from Nerney et al. (2020) taking the “cubic centimeter” physical chemistry model at 6 RJ (that matches conditions derived from the Cassini UVIS spectrum) as typical of the main torus. The model is not very sensitive to the temperature of the hot electrons (40-400 eV). Model inputs are: O/S source ratio =1.9, source of neutrals \(S_n=6.4 \times 10^{-4}\) cm\(^{-3}\) s\(^{-1}\), transport timescale= 64 Days, fraction of hot electrons \(f_{eh} = 0.25\%\), temperature of hot electrons \(T_{eh}=46\) eV. This neutral production rate is equivalent to a net neutral source of 575 kg/s for a volume of 68 RJ\(^3\). Nerney et al. (2020) call this the “low & slow” case. Similar results are found for a high source rate of 1.8 ton/s (\(S_n=20 \times 10^{-4}\) cm\(^{-3}\) s\(^{-1}\) over a volume of 68 RJ\(^3\)) and correspondingly shorter transport times – the “high & fast” case. Note that there is an anticorrelation of transport time and source to match the observed density (~2000 cm\(^{-3}\)) in the torus.

The “low & slow” example is shown in Figure 16a. Sulfur is more easily ionized than oxygen so that the dominant sulfur ion becomes S\(^++\) while oxygen is quickly charge-exchanged and much (42\%) of the oxygen is lost from the region as fast neutrals. Hence the abundance ratio of the dominant (M/Q=16) ions O\(^+\)/S\(^++\) is about unity and we expect a denser, more extensive neutral oxygen cloud (density \(~50\) cm\(^{-3}\)) than neutral sulfur cloud (density \(~11\) cm\(^{-3}\)), consistent with recent modeling by Smith et al. (2019) discussed in section 4.1 above. The S\(^+\), S\(^+++\) and O\(^++\) ions, with abundances of a few percent each, are transported out of the torus with the dominant O\(^+\) and S\(^++\) ions. The suprathermal electrons contribute to ionization, particularly for the higher ionization states, but the thermal electrons play the major role in the particle budget overall. The hot electrons become more important when considering the energy budget.

Figure 16b shows the flow of energy through the system for the “low & slow” case. Here hot, suprathermal electrons play a major role, supplying 63\% of the energy. Current physical chemistry models fix the contribution of hot electrons to the total density. This is a simplistic approach and we await more sophisticated models. Nevertheless, such an approach provides...
useful indications of the extent of the role played by supra-thermal electrons. The model is very sensitive to the fraction of hot electrons and Nerney et al. (2020) could not find realistic physical chemistry solutions for $f_{eh} > 0.5\%$. Additional energy sources are from ion pick up of $S^+$ (16%) and $O^+$ (18%) ions. Most of this energy input to the torus is coupled via Coulomb collisions to the core, thermal electrons and radiated out via mostly UV emissions (91%) excited by electron impact.

The mass flow for “high & fast” case is remarkably similar with a slightly lower average ionization state since there is less time to ionize the higher source of neutrals beyond the first ionization state. The energy flow for “high & fast” case requires fewer hot electrons (~40% of the energy supply) with the higher neutral source producing more pick-up ions. The ions remain 30-40eV hotter, carrying more of the energy out of the system with less (73%) being radiated through UV emissions. Note that both “low & slow” and “high & fast” cases are matching typical torus conditions and emissions.

Estimates of the hot electron fraction based on UV emissions range from <1% to 15% (Steffl et al. 2004a,b; Yoshioka et al. 2014, 2017, 2018; Nerney et al. 2017; Tsuchiya et al. 2017, 2019; Hikida et al. 2018) with the fraction increasing from 6 to 8 R$_J$. Physical chemistry models consistently suggest less than 1% (typically ~0.25%) for the hot electron fraction necessary to power the torus at 6 R$_J$ (Delamere & Bagenal 2003; Yoshioka et al. 2011) increasing to 1.5% at 9 R$_J$ (Delamere et al. 2005). Nerney et al. (2020) shows that one can match the UV emission spectrum with a range of $F_{eh}$ from 0.1 to 5%, far higher values than suggested by the physical chemistry limits (<0.5% at 6 R$_J$). In situ measurements from Voyager PLS electron data show electron distributions that reasonably approximate a double Maxwellian for most of the torus. Beyond about 8 R$_J$ the supra-thermal component increases, forming a tail to the thermal core. Sittler & Strobel (1987) derive values for the hot electron fraction of (0.15, 0.9, 10%) at (6, 8, 9 R$_J$) respectively.

While the need for a supply of supra-thermal electrons has been known since the mid-80s, the source mechanism remains unknown. It is even debated whether they are produced locally within the fluxtubes connected to the torus (Hess et al. 2011a; Copper et al. 2016) or injected from the outer magnetosphere (Yoshikawa et al. 2017; Tsuchiya et al. 2018, 2019; Kimura et al. 2018). The Galileo flybys of Io showed that beams of supra-thermal electrons are produced in the wake of the Io interaction (reported by Frank & Paterson (1999) and discussed in section 3.1 above) but these beams are confined to a limit region and are not sufficient to power the whole torus. Furthermore, no significant Io-modulation was found in the Voyager or Cassini UV emissions from the torus (Sandel & Broadfoot 1982a,b; Steffl et al. 2004a,b). In the more recent and extensive monitoring of UV emissions by Hisaki, Tsuchiya et al. (2015) reports a ~10% modulation of the UV power associated with the phase of Io’s orbit.

**Spatial Variations and Modulations.** Over the past forty years spatial and temporal variations of the Io plasma torus have intrigued observers and puzzled theorists. For the warm torus, there are four main types of variations: (A) System III longitude variations at Jupiter’s spin period tied to the magnetic field structure; (B) a pattern/perodicity that drifts at a few percent slower than System III, originally called System IV; (C) temporal variations associated with Io’s volcanic eruptions; (D) modulations in brightness of torus emissions and a radial shift of the peak location on the dawn vs. dusk side of Jupiter.
The idea of a systematic longitudinal modulation of the magnetosphere of Jupiter was initially provoked by *Pioneer* observations of energetic electrons escaping the system with a 10-hour periodicity (Chenette et al. 1974), which Dessler (1978) interpreted as due to an anomalously weak field at a specific longitude driving preferential outflow in this “magnetic anomaly” region (Dessler & Vasyliunas 1979; Vasyliunas & Dessler 1981). From 1980 onwards ground-based observations of optical emissions from S+ ions showed systematic longitude variations (see thorough review in Steffl et al. 2006). *Voyager* UV emissions showed longitudinal variations in S+ and S++ emissions (Sandel & Broadfoot 1982b; Herbert & Sandel 2000) while Lichtenberg et al. (2001) found similar variations in IR emissions from S+++ ions. The 45 days of monitoring the UV emissions from multiple ions in the torus by the *Cassini* UVIS instrument in late 2000 allowed Steffl et al. (2006) to analyze the temporal variability of the main Io torus. The primary effect they found was a System III longitude ~25% modulation of S+ and S+++ emissions (anti-correlated) that is consistent with a longitudinal modulation of electron density ~5% and temperature ~10%. The primary ion species, S++ and O+ showed only few percent modulation. Steffl et al. (2008) modeled these emission modulations with a “cubic centimeter” physical chemistry model, taking the fraction of hot electrons around a baseline value of 0.23% of the total electron density and superposing a 25% variation with longitude, peaking at 290° longitude. This small change in the hot electron fraction is enough to alter the ionization state of sulfur ions.

Hess et al. (2011a) showed that such a modulation of hot electrons could be explained by Alfvénic heating of electrons close to the jovian ionosphere and a longitudinal variation (due to the non-dipole components of Jupiter’s magnetic field) of the magnetic mirror ratio – that is, the ratio of the magnetic field in Jupiter’s ionosphere to the field strength at the magnetic equator. They showed that the VIPAL magnetic field model of Hess et al. (2011b) has a strong longitudinal dependence of the magnetic mirror ratio (averaged between north and south hemispheres) with a peak at 280° System III longitude. The Juno-based JRM09 magnetic field model of Connerney et al. (2018) shows an even larger peak at the same longitude. Such a peak in magnetic mirror ratio around 280° longitude means fewer hot electrons are scattered by waves into Jupiter’s ionosphere at such longitudes. Thus the geometry of Jupiter’s magnetic field is able to explain the small enhancement of hot electrons that is able to modulate the abundances – and hence emissions – of S+ and S+++ ions.

The second longitudinal modulation of the torus emissions – the System IV variation – is more complicated. Hints of variations on a timescale a few percent longer than System III came from radio emissions (Kaiser & Desch 1980, Kaiser et al. 1996) and ground-based emissions (Roesler et al. 1984). Sandel & Dessler (1988) noted that the *Voyager* UV emissions had a periodicity at 10.22 hours, a few percent longer than Jupiter’s 9.925-hour System III spin rate, which they labelled System IV. Brown (1995) found a similar (10.214 hour) periodicity in ground-based S+ emissions, but noted that the phase of this System IV sometimes shifted (also noted by Reiner et al. 1993; Woodward et al. 1994, 1997). Steffl et al. (2006) found a periodicity in the *Cassini* UVIS data of 10.07 hours, just 1.5% longer than the System III. Steffl et al. (2008) were able to model the 45 days of emission modulation as a compositional wave propagating azimuthally around the torus, driven by a combination of two sinusoidal variations in hot electron fraction about an average value (0.235%): a 30% modulation with a peak at 290° System III longitude, plus a 43% modulation drifting 12.5°/day (System IV). The beating of these two modulations produced peak amplitude with a 29-day beat frequency. The Steffl et al.
(2006, 2008) analysis of the UVIS data provides an empirical description of the System III/IV modulations but does not explain them.

Copper et al. (2016) adapted the Delamere et al. (2005) physical chemistry model of the torus allowing variation in two-dimensions: radial distance and azimuth. They simulated the UVIS variations in $S^+/S^{++}$ abundance ratio by applying a System III variation in hot electron fraction (consistent with the Hess et al. (2011a) Alfvénic heating plus magnetic field asymmetry enhancing trapping of hot electrons at $280^\circ$) for all radial distances and then imposed subcorotation of $1$ km/s ($\sim 12^\circ$/day) at $6$ RJ, increasing to $4$ km/s at $7$ RJ and then decreasing to full corotation at $10$ RJ (approximating the radial profile of subcorotation observed by Brown 1994). The model simulated the System III/IV beat structure found by Steffl et al. (2006) for the densest (and brightest) part of the torus ($6-7$ RJ) with the System IV effect fading out beyond $\sim 7$ RJ. This behavior provides compelling evidence that the physics of magnetosphere-ionosphere coupling is key to the System IV variations. The short-term changes in the System IV period (on timescales of months to years) mean it is unlikely that this erratic modulation stems from changes in the intrinsic planetary magnetic field as originally suggested by Sandel & Dessler (1988), analogous to the changing solar magnetic field. Instead, variations in thermospheric/ionospheric properties and/or variations in plasma torus properties driven by iogenic input likely play an important role.

Temporal variations in the torus emissions suggest Io’s volcanic eruptions can drive changes in the plasma torus. There are multiple observations of changes in the amount of neutral gas and plasma escaping from Io (Brown & Bouchez 1997; Bouchez et al. 2000; Mendillo et al. 2004; Nozawa et al. 2004, 2005, 2006; Steffl et al. 2004b; Delamere et al. 2005; Yoneda et al. 2010, 2015; de Kleer & de Pater 2016; Koga et al. 2018a,b,2019; Morgenthaler et al. 2019; Schmidt et al. 2018). But it is still difficult to predict the timing, duration, and spatial extent of the changes in the neutrals and plasma – let alone relate such changes to specific volcanic activity. The transport of plasma from the Io plasma torus has been estimated to take tens of days (Delamere & Bagenal 2003; Bagenal & Delamere 2011). To investigate the magnetosphere response to changes in the plasma supply rate from Io, it is essential to monitor both changes in the neutral cloud around Io as well as the plasma conditions in the torus. As Cassini approached Jupiter, the Galileo dust instrument reported a 1000-fold increase in dust production, assumed to be caused by volcanic eruptions on Io (Kruger et al. 2003). The dust outburst began in July 2000, peaked in September and settled back to normal by December 2000, overlapping with reports of activity from Io’s Tvashtar volcano (Milazzo et al. 2005). The Cassini UVIS instrument started observing UV emissions from the Io torus in October 2000 and Steffl et al. (2004b) reported high intensities that dropped to normal values by the end of the year. Delamere et al. (2004) matched the changing UV emissions from the torus reported by Steffl et al. (2004b) with a factor $\sim 3$ increase (significantly less than the dust increase) in source of iogenic atomic neutrals lasting about 3 weeks, peaking at about August 2000. By January 2001, the torus seemed to have relaxed back to more typical conditions. Why the gas production in the torus was only a factor of $\sim 3$ while the dust production increased by three orders of magnitude remains a mystery.

The JAXA Hisaki satellite has produced quasi-continuous EUV spectral images of planetary exospheres since its launch in 2013 (Yoshikawa et al. 2014). Emissions from the warm outer torus show similar features to those of Cassini UVIS: dawn-dusk asymmetry, a System III longitude modulation by hot electrons, plus a strong modulation by the phase of Io (Yoshioka et al. 2014; Tsuchiya et al. 2015). In addition to continually monitoring the Io plasma torus
emissions the *Hisaki* instrument has made a spectacular measurement of the neutral atomic oxygen cloud spreading all around Io’s orbit (Koga et al. 2018a,b), which is discussed further in section 4.1 above.

Conveniently, Io had a major volcanic event in mid-2015 (perhaps in part associated with the eruption of Kuradalagon Patera observed in the NIR by de Kleer & de Pater 2016, 2017) and *Hisaki* was able to measure the response in the emissions of different ion species in the Io plasma torus (Tsuchiya et al. 2015, 2019; Yoshikawa et al. 2017; Kimura et al. 2018; Yoshioka et al. 2018). In particular, Yoshiokoka et al. (2018) compared the *Hisaki* torus emissions at the peak of the enhancement (DOY 50 2015) with quiet-time (late 2013) to which they applied a physical chemistry model to derive a factor 4.2 increase in neutral source, a ~2-4 times faster radial transport rate, and a minor increase in hot electron fraction (from 0.4% to 0.7%). Hikida et al. (2019) argue that the hot electron fraction was particularly enhanced on the dusk side. Yoshioka et al. (2018) also found a reduction in the O/S ratio of the neutral source (from 2.4 to 1.7), consistent with the analyses of an active period in the *Galileo*-era by Nerney et al. (2017) and by Herbert et al. (2001).

Copper et al. (2016) explored the effects of increased mass-loading on their 2-dimensional model, comparing with the mid-2015 *Hisaki* event. They found they could model the observed general changes in plasma conditions (enhanced emissions, adjustments of composition) with an enhanced (x2.4) plasma source, increased hot electron fraction and decreased radial transport time (43 to 34 days). Tsuchiya et al. (2019) collected *Hisaki* measurements of S+++ and S+ emissions over three seasons (the first halves of 2014, 2015, 2016) to derive S+++/S+ emission ratio variations with System III and IV. They show a shortening of the System IV period after periods of volcanic activity, with an exception of an anomalous change in February 2014 that was associated with a change in Io’s volcanic activity.

Suzuki et al. (2018) made a time-series analysis of the total EUV emission from the torus observed by *Hisaki* to explore the lifetime of brightenings that occur on top of System III and IV modulations. They applied the technique of Volwerk et al. (1997) who derived a radiative timescale for torus emissions of <5 hours from *Voyager* UVS data by comparing emissions between dawn and dusk as the plasma torus rotated around Jupiter every 10 hours. Suzuki et al. (2018) applied the Coulomb collision rate for hot electrons heating the thermal electron population to derive the temperature of a fixed 0.4% fraction of hot electrons. Out of 42 brightening events in 240 days of observation over December 2013 to May 2015, they found that the majority (83%) did not persist for 5 hours, suggesting that the hot electrons were colder than 150 eV. The remaining 7 events (17%) persisted for longer than 5 hours, consistent with suprathermal electron energies of 270-530 eV.

The fourth variation of the Io plasma torus is an apparent radial shift and intensity modulation with local time. Ground-based observers measuring optical torus emissions (primarily from S+ ions) noticed that the peak of the plasma torus emission appeared shifted by about 0.2 RJ towards the dawn side of Jupiter (i.e. to the east in the night sky as observed from Earth) compared to the dusk side (i.e. west in the sky) (Morgan 1985a,b; Oliversen et al. 1991; Schneider & Trauger 1995). Observers measuring UV emissions noticed that the plasma torus emission intensity was usually stronger on the dusk side of Jupiter than the dawn side by as much as a factor of 2 (Sandel & Broadfoot 1982b). This dawn-dusk asymmetry was explained by plasma flow down the magnetotail imposing a dawn-dusk electric field across the magnetosphere (Ip & Goertz 1983; Barbosa & Kivelson 1983). As the torus plasma moves around Jupiter, the
electric field causes the plasma to move a few percent closer to (farther from) Jupiter on the dusk (dawn) side. Just a small shift produces sufficient compression (enhancing density) and heating on the dusk side, to double the UV emission. The Voyager UVS instrument resolved the spatial structure of the inner edge of the warm torus, indicating that 80-85% of the emission came from the narrow (0.2 RJ wide) ribbon region that showed this strong dawn-dusk asymmetry (Sandel & Broadfoot 1982b; Volwerk et al. 1997). The Cassini UVIS measurements showed a similar dusk/dawn emission ratio (1.3 ± 0.25) but did not resolve the narrow ribbon (Steffl et al. 2004a,b). The 3 years of Hisaki emissions show a similar dusk/dawn emission ratio but also reveal a modulation by the phase of Io in its orbit around Jupiter (Tsuchiya et al. 2015, 2019; Murakami et al. 2016), suggesting that local heating of electrons in Io’s wake is involved in the local time modulation.

Thus, the four types of variations in the warm plasma torus (6-8 RJ) are indications of the processes that modulate the flow of mass and energy through the system. The bulk (~90%) of the plasma that comes from Io fills the warm plasma torus, and spreads out into the vast magnetosphere of Jupiter. We consider the 10% diffusing inward and the narrow spatial region around Io’s orbit and in the next section.

5.3 Inner Io Plasma Torus: Ribbon & Washer

The inner boundary to the warm torus is a narrow (width~0.2 RJ), often bright region called the “ribbon”, the location of the peak emission varying with local time between 5.6 and 5.9 RJ. This ribbon has a similar vertical extension as the warm torus, suggesting it may just be the inner boundary of the main torus (Figure 14, Table 5). Inward of the ribbon, the plasma is much colder (T_e and T_i both dropping to <1 eV), forming a thin (H~0.2 RJ), washer-shaped disk between 5.6 and 4.7 RJ that is thought to be relatively stable over time.

For the post-Voyager era the plasma properties inside Io’s orbit could be characterized (Bagenal 1985) by three regimes: (1) the ribbon (6.0 – 5.6 RJ) of high density plasma population where the ion distributions have substantial non-Maxwellian tails implying the presence of pick-up ions, a bulk speed with ~5% lag behind corotation, electrons a factor ~5 times colder than the ions; (2) a “gap” or “dip”(5.6 -5.4 RJ) where there are sharp drops in both density and temperature (illustrated in panel (d) of Figure 17), shown by Schmidt et al. (2018) to vary with longitude; (3) the cold, inner torus (< 5.4 RJ) where the bulk flow is close to corotation, the ion and electron species are in close thermodynamic equilibrium with dwindling supra-thermal components (panel (b) of Figure 17). The difference in plasma conditions in these regions and the sharp boundaries suggest that the structure of the inner torus cannot be explained in terms of simple models of steady radial diffusion.

The thin, bright ribbon is most distinct in optical emissions of S⁺ ions, as illustrated in Figure 17. The brightness reflects a combination of high density (~3000 cm⁻³) and high abundance of S⁺ ions. Farther out in the warm torus the presence of warmer electrons raises the sulfur ionization state with S⁺⁺ ions becoming dominant. Both in situ measurements and high-resolution optical emission spectra show the electron and ion temperatures plummet inside ~5.7 RJ and the dominant S⁺ and O⁺ ions become tightly confined to the centrifugal equator. The greatly reduced temperatures inside ~6 RJ complicates observations of the inner torus. The colder temperatures cut off the UV emissions while the optical emissions from the tenuous inner regions are hard to observe along a line of sight through the dense ribbon region.
Just as in the main, warm plasma torus, the ribbon is modulated by System III, System IV, local time and volcanic activity. For example, Schneider & Trauger (1995) report a variation in parallel (“vertical”) temperature with System III longitude. But the tight radial confinement of the ribbon means that of particular importance is the dawn-dusk shift of the plasma by ~0.2-0.3 RJ due to the global electric field, moving the center of the ribbon from 5.84 ± 0.06 RJ on the dawn side to 5.56 ± 0.07 RJ on the dusk side (Morgan 1985a,b; Schneider & Trauger 1995; Herbert et al. 2008; Smyth et al. 2011; Schmidt et al. 2018). This shift is comparable to the width of the ribbon and moves this region of peak emission relative to Io’s orbit (5.90 ± 0.024 RJ where 1 RJ=71,492 km). The ribbon occupies a volume that overlaps the cloud of neutrals from Io, the source of the plasma torus. Thus, these spatial and temporal variations of the ribbon may be influencing – or influenced by – the plasma source.

Furthermore, the ribbon is associated with a 5% dip in the azimuthal flow of the plasma relative to corotation (Brown 1994; Thomas et al. 2001). The dip is lowest at ~6-7 RJ (indicating the peak plasma source region with high mass-loading), rising back up to corotation by Europa. Inside 5.4 RJ the plasma was sufficiently cold for the Voyager PLS instrument to resolve separate ion peaks and determine that the plasma flow in the cold torus is within 1% of corotation.

Little progress was made in modeling the inner torus until Herbert et al. (2008) reanalyzed the Schneider et al. (1991b) observations of S+ emission and derived a quantitative description of the ribbon plus cold inner torus, including variations with local time and System III (further quantified using Galileo data by Smyth et al. 2011). Herbert et al. (2008) reported that the scale height of the ribbon (proportional to the S+ temperature parallel to the magnetic field, between 20-100 eV) varies over longitude and time. They also report a vertical offset from the centrifugal equator with longitude that is probably due to the fact that with the very low temperatures and small (<0.2 RJ) scale height, the location of the centrifugal equator is sensitive to high-order structure of magnetic field (as noted by Bagenal 1994). The high-order structure of Jupiter’s magnetic field derived from Juno’s close flybys of the planet (Connerney et al. 2018) may allow accurate modeling of such fine-scale features. The red line in Figure 17 shows latest magnetic field model is close but does not yet match on the fine spatial scale of the cold inner torus.

Richardson & Siscoe (1981, 1983) first tried to address the issue of the flow of mass and energy inside Io’s orbit with a diffusive transport model and concluded that (i) the steeper gradient in fluxtube content inside the ribbon meant that the plasma diffuses inwards ~50 times slower than outwards; (ii) additional sources of both plasma and heat were needed in the cold torus. These early studies were hampered by lack of information about the neutrals, limited physical chemistry data, as well as the fact that the first reports of ion temperature from Voyager PLS were over estimated by a factor of 2 (Bagenal et al. 1985). Subsequent models (Moreno et al. 1986; Barbosa & Moreno 1988; Herbert et al. 2001) still needed an additional local source of energy.

One source of mass and energy in the inner torus could be molecular SO2 coming from the Io interaction either as neutrals or ions (see section 3.1). The molecular ion SO2+ has been observed directly (Figure 17b) by Voyager PLS in the cold torus (Bagenal et al. 1985; Dougherty et al. 2017). The molecular ion has not been detected in the warm torus, partly because it is likely quickly dissociated and/or recombined but also because the heavy, molecular ion species is likely swamped by the supra-thermal tail of the major atomic ion species in the PLS spectrum. Further evidence of molecular ion species came from magnetic signatures measured on multiple flybys.
of Io by *Galileo*. To quote Russell (2005): “The existence of ion cyclotron waves at the SO$_2^+$ and SO$^+$ gyrofrequencies (Kivelson et al. 1996b; Russell & Kivelson 2000) was not so much a surprise in the *Galileo* data as were their amplitudes and spatial extent”. Analysis of such waves by Huddleston et al. (1997, 1998) and Blanco-Cano et al. (2001) showed these molecular species extend for many Io radii and correspond to a source of 8 x 10$^{26}$ SO$_2^+$ ions/s. Models by Smyth & Marconi (1998) and by Cowee et al. (2003, 2005) showed that SO$_2^+$ could contribute to the source of plasma needed in the inner torus. Nevertheless, the lack of remote sensing of these molecular species means that the spatial distribution of such molecular species is poorly constrained.

While the relatively small volume and mass of material residing inside Io’s orbit plays a limited role in the total magnetosphere, there are major unresolved issues about spatial and temporal variability of these fine-scaled structures that could tell us about the nature of the source of neutrals and plasma from Io.

5.4 Influence of Europa on Plasma

Figure 15 shows that the UV emissions from the plasma torus indicate rising electron temperatures and increasing amounts of ions with higher ionization states as the plasma moves out from Io towards Europa’s orbit. But there does not seem to be an enhanced plasma density nor change in ion composition associated with Europa. This is perhaps not surprising given the relatively small (~25-70 kg/s) escape rate of neutrals (mostly H$_2$) from Europa (see sections 3.2 and 4.2). Delamere et al. (2005) applied such a source around Europa’s orbit to their physical chemistry model and found very modest (few percent) changes in the ion abundances (increasing O$^+$, decreasing S$^{n+}$). The most significant impact of a Europa source is the production of pick-up ions (650 eV for locally produced O$^+$ ions) that enhances the ion temperature. Unfortunately, it is not easy to differentiate between heating due to ion pick-up around Europa’s orbit with the general heating via as-yet unknown processes that seems to be operating on the plasma as it moves outwards through the magnetosphere.

The most significant impact of Europa on the magnetosphere of Jupiter is likely the effect of the neutral clouds on the inwardly diffusing energetic particle populations, as discussed in the next section.

5.5 Energetic Particle Fluxes

While we focus in this paper on the thermal plasma populations (that dominate the density of charged particles), the supra-thermal particles (electrons, protons, heavy ions) play important roles as they interact with the moons, the neutral clouds and thermal plasma. Being light, electrons are relatively easy to accelerate to high energies via various wave-particle interactions (see review by Thorne 1983). Accelerating ions, particularly heavy O and S ions, is more of a challenge. To quote Mauk et al. (2004): “Heavy ions are thought to begin life as cool ions in the inner magnetosphere, diffuse outward to the middle magnetosphere, become energized there through nonadiabatic, invariant-violating processes, and then diffuse back into the inner magnetosphere, gaining additional energy through conservation of adiabatic invariants. The two important characteristics of Jupiter’s middle magnetosphere that promote particle energization are its fast rotational flows, and associated radial electric field, and its neutral sheet (i.e. current sheet) geometry.”
Figure 18 shows profiles between 5 and 15 R\textsubscript{J} of thermal plasma density (top panel, based on Voyager), fluxes of ~100 keV ions (H\textsuperscript{+}, S\textsuperscript{n\textsuperscript{+}}, O\textsuperscript{n\textsuperscript{+}}) and electrons (middle panel). The bottom panel of Figure 18 compares fluxes of O\textsuperscript{n\textsuperscript{+}} ions at different energies (measured by the Galileo EPD instrument). The population of energetic electrons monotonically increases as they move inwards through the Io-Europa region (Jun et al. 2005; Nenon et al. 2017). Note that all ion species in Galileo EPD data show a sharp drop as they move inwards past Europa’s orbit (Lagg et al. 1998, 2003; Kollmann et al. 2016; Nenon et al. 2018; Nenon & Andre 2019). This structure is primarily due to charge-exchange reactions of the inward-moving energetic ions with the neutral clouds of Europa and Io (illustrated in Figure 13 from the modeling of Smith et al. 2019). Energetic particles are particularly sensitive to neutral gas clouds because their bounce motion carries them frequently through the cloud, while lower energy ions pass and interact less often. Inside Europa’s orbit oxygen ions are preferentially removed because (a) they are primarily singly-charged so that a CHEX reaction produces an ENA that is lost from the system, and (b) there is more neutral oxygen (Figure 13) for resonant CHEX reactions. Mauk et al. (2004) suggest that the H\textsuperscript{+} profile flattens around 7 R\textsubscript{J} due to local wave heating of protons, but eventually charge exchange with the Io neutral cloud causes the protons to plummet towards 6 R\textsubscript{J}. The prevalence of higher ionization states of sulfur means that most incoming energetic S ions need to undergo more than one CHEX reactions before being lost as vENAs (Clark et al. 2016; Allen et al. 2019).

The bottom panel of Figure 18 demonstrates the energy dependence of ion loss via charge exchange. Energetic oxygen is efficiently lost via charge exchange with neutral atomic oxygen clouds at energies near or below 100 keV. The charge exchange cross section drops steeply above 100 keV. At 100 keV the fluxes drop inside of Europa’s orbit, while 1.5 MeV oxygen ions are transported farther inward before being lost closer to Io.

Lagg et al. (1998) used ion fluxes to measure Io plasma torus densities from energetic particle pitch-angle distributions. The factor 100 drop in proton intensities at Io is from scattering by local electromagnetic ion cyclotron waves, perhaps excited by local ion pick-up (Nenon et al. 2018). Mauk et al. (2004) points out that the fluxes of energetic ion fluxes between Europa and Io measured by Galileo (specifically 1995-1999) were lower than measured by Voyager in 1979 and suggests that this may be consistent with enhanced neutral cloud densities for the Galileo period observed by Wilson et al. (2002) causing enhanced energetic particle losses via charge-exchange.

6 Jovian Neutral Nebulae

Since the early (pre-Voyager) detection of the sodium cloud near Io, there has been the realization that charge exchange of Io torus ions could generate a wind of neutrals extending out into the magnetosphere and might be a source of plasma (Eviatar et al. 1976). The Voyager measurements of energetic sulfur and oxygen ions in the middle magnetosphere fed the idea that re-ionization of such iogenic neutrals could produce pick-up ions at 10s of keV energies, gaining further energy as they diffused inwards (Cheng 1980; Eviatar & Barbosa 1984; Barbosa & Eviatar 1986). It was also realized that such a wind of neutrals might supply heavy ions upstream of Jupiter (Krimigis et al. 1980; Kirsh et al. 1981; Baker et al. 1984). As it skims over Jupiter’s ionosphere, the Juno spacecraft is now showing heavy ions at both low (Valek et al. 2019a,b) and high (100s keV in Kollmann et al. 2017) energies. Perhaps these ions come from sprays of Io and/or Europa neutrals impacting the jovian atmosphere.
Below we briefly summarize the limited knowledge we have about these neutral nebulae and the roles they may play.

6.1 Mendillo-Disk – Io ENAs

By the late 80s it was realized that sodium atoms escaping from the Io environment could span many degrees across the sky, and could be imaged by wide-field cameras designed to study the Earth’s atmospheric emissions. Mendillo et al. (1990) reported emission extending >400 R\text{J} from Jupiter in a disk (Figure 12). They proposed that sodium ions in the Io plasma torus charge exchange with neutrals around Io’s orbit. This means that when neutralized via charge-exchange the atoms spray mostly outwards in a disk of neutral atoms with energies of ~400 eV. To honor the discoverer, we call this nebula the “Mendillosphere” or “M endlodisk”. Flynn et al. (1994) modeled two-years of observations of the extended sodium nebula and found that the flaring angle of the disk (20-27°) anti-correlated with the source production rate (as indicated by Io’s surface IR output or brightness of near-Io emissions). Studies of Io’s extended neutral clouds showed variations with local time and Io’s orbital phase (Mendillo et al. 1992, 2004; Flynn et al. 1994; Yoneda et al. 2015) and a source of 1-4 x 10^{26} atoms per second. Mendillo et al. (2004; 2007) show a variation in brightness and shape with Io’s volcanic activity – the disk having angular edges (like an anulus) when Io is particularly active compared with an oblate spheroid during quiet times. The suggested explanation is that under quiet times the sodium ENAs are produced (from neutralized Na^+ in the torus) as a stream (Figure 12). When Io is more active, production as jets local to Io increases, e.g. via dissociative recombination of molecular sodium ions such as NaCl^+ (Mendillo et al. 2007).

Similar extended disks of escaping S and O atoms, as well as SO\textsubscript{2} and SO molecules also probably exist. Physical chemistry models of the torus (e.g. Delamere et al. 2005) predict charge exchange processes will produce a flux of escaping neutralized atoms of 1-5 x 10^{28} atoms per second, mostly oxygen (Figure 16a). While this is ~100 times greater than the sodium flux, the radiation efficiency of other species is so much weaker that any neutral disk would be very hard to detect. Direct in situ detection of these escaping neutrals would require an instrument that measures ENAs with energies less than ~300 eV (e.g., <20 eV/nucleon for oxygen atoms moving at 70 km/s).

While corotating torus ions that are neutralized via charge exchange with Io’s neutral clouds will come off as an outward stream, charge exchange close to Io could come off as a jet or spray (Figure 12). For example, a recently-picked-up ion produced in the plasma-atmosphere interaction that charge exchange could be directed towards Jupiter where re-ionization on impacting the planet’s atmosphere would be a source of cold heavy ions in the planet’s ionosphere.

6.2 Spherical Neutral Nebula – Europa vENAs

On route to Saturn, Cassini flew past Jupiter for a gravity assist in late 2000. Cassini carried an instrument that detected vENAs, initially assumed to be hydrogen atoms, in the range of 50-80 keV emanating from what appeared to be Europa’s orbit (Krimigis et al. 2002). Note the difference between these (very energetic) 10s keV/nucleon atoms from the ioogenic ENAs with ~200 eV – few keV. Mauk et al. (2003, 2004) modeled these vENAs as products of charge exchange reactions of inward-moving energetic (10s keV) protons with neutrals in a cloud surrounding Europa’s orbit (Figure 19). The observed flux of vENAs (10^{25} s^{-1}) requires a local
density of 20 to 50 cm\(^{-3}\) of neutrals in the Europa neutral cloud (see Section 4.2 above). Mauk et al. (2004) assumed these neutrals were atomic hydrogen (based on the model of Schreier et al. 1998) but the updated Smith et al. (2019) model suggests the primary neutral species is molecular H\(_2\) (Figure 13).

Note that the ions charge exchanging with the Europa neutral cloud are sufficiently energetic that their bulk motion is much less than their thermal or gyro motion (V\(_{co}\ll Vg\)). This means that the ion velocities combine gyro and bounce motions that span most of 4 \(\pi\) in directions. Thus, when they become neutralized, the Europa vENAs spray pretty much equally in all directions, forming a spherical cloud (Figure 20), unlike the torus ions motion that is mostly corotational so that the iogenic ENAs, which form a disk (“Mendillodisk”).

6.3 Re-ionization Upstream of Jupiter

Krimigis et al. (2002) showed a plot (Figure 20) of ions measured by the Cassini CHEMS instrument in the solar wind upstream of Jupiter indicating the presence of energetic (55-220 keV) oxygen and sulfur ions (as well as possible Na\(^+\) and SO\(_2^+\) ions), which they ascribe to photo-ionization of the escaping ENAs. The Cassini measurements of heavy ions upstream of Jupiter add to measurements by Voyager (Krimigis et al. 1980; Kirsh et al. 1981; Baker et al. 1981) and Ulysses (Haggerty et al. 1999), but it is not clear at this point in time how much these ions leak out of the magnetosphere as energetic ions (Mauk et al. 2019) vs. produced locally via re-ionization of escaping neutral atoms, whether Io-ENAs or Europa-vENAs.

7 Conclusions

The peculiar role of Io in the magnetosphere of Jupiter was first noticed in 1964. A half century and a thousand or so papers later it is a good time to consider our understanding of the system and what are the key open questions. First, we consider the individual components of the system and then address coupling between them.

7.1 Outstanding Issues

Atmospheres. The tenuous atmospheres of Io and Europa are hard to study remotely and close-up observations are often selective in viewpoint, coverage, and gas components. From a planetary atmosphere perspective, the main focus is often properties near the surface. From a space physics perspective, we are more interested in the outer regions. Specific open questions are:

- What are the radial, latitudinal and longitudinal distributions, plus composition of the neutral atmospheres of Io and Europa from the surface to high altitude in daylight, in eclipse and at night?
- How do the atmospheres, particularly the upper regions, vary with volcanic activity of the moon? How does the location of any active sites alter the plasma-atmosphere interaction?
- Why is Io’s atmosphere sometimes very stable for many years then suddenly seems to supply large amount of neutrals, dust to the Io environment?
- How much of the ionospheric density (e.g. as observed via radio occultations) is produced via photoionization vs. plasma impact on the atmosphere, and/or material
• Where is the exobase? A specific height is not a correct description for the complex interactions at Io and Europa. Moreover, the exobase certainly varies with latitude and longitude on the moon, plasma flow direction, solar illumination, and likely with magnetic latitude of the moon in ways that are difficult to quantify with disparate sets of measurements and models.

**Plasma-Atmosphere Interactions.** The aurora produced via electron bombardment of the atmosphere can provide useful information about the interaction of the surrounding plasma with a moon’s atmosphere. But to explore the full physics we need a combination of in situ measurements along close flybys and detailed modelling. Specific open questions are:

• How much of the plasma interaction goes into heating the atmosphere? Where? What is the impact on the atmospheric distribution?

• What are the roles of electron impact ionization, charge exchange, collisions, and electron beams in the plasma-atmosphere interaction? What are the net ionized products of these reactions that escape into the space beyond?

• What are the composition, velocity distribution, and fluxes of the neutrals that escape the moon’s gravity and into the space beyond?

• How do the plasma interactions vary around the moon (e.g. upstream vs. downstream, sub/anti-Jupiter, day/night), with magnetic latitude and longitude and with local time / phase of the moon along its orbit?

• For each moon, what is the strength of the internal induction signal compared to ionospheric perturbations in the fields and flow? How much from the conducting ocean/asthenosphere and/or the core?

• How much of the iogenic material reaches the surface of Europa?

• How do the plasma interactions vary (qualitatively and quantitatively) with volcanic activity of the moon? What types and/or locations of volcanos affect the interaction?

• How do seasonal changes in distance from the Sun (that drives sublimation and photoionization rates) modify the plasma-atmosphere-ionosphere interaction?

**Neutral Clouds.** While alkali elements are clearly observed around both Io and Europa, the major species are poorly measured, except Io’s oxygen cloud that is now being mapped out by the *Hisaki* mission. Specific open questions are:

• What are the amounts and trajectories of different neutral species that escape Io and Europa? In particular, are there molecular clouds of SO₂, SO, O₂, H₂, OH? What roles do they play? Is there a way to detect them? Are there any features in other atomic and molecular neutral clouds similar to the Na neutral structures such as jets, streamers and the extended Mendillo-disk?
• How are these neutral clouds shaped by the plasma that flows through them? At Io, how much of the neutral clouds reach inwards of Io’s orbit (as molecules and/or atoms) to provide an extended source for the ribbon and inner torus? At Europa, how do the neutral clouds change under the variable conditions in the outer torus?

• What role do the neutral clouds play in controlling the influx of energetic particles (electrons, protons and heavy ions) from the middle magnetosphere through to the radiation belts within a few RJ of Jupiter?

**Plasma Torus and Sheet.** The general structure and systematic modulations (System III, IV, local time) of the three components of the torus – cold inner torus, ribbon, warm outer torus and plasma sheet – are fairly well described but underlying physical processes remain unclear. Specific open questions are:

• What is (are) the source(s) of hot electrons? Do waves within the torus accelerate local electrons? Are hot electrons injected from outside?

• How is plasma heated as it moves out from the torus to the plasma sheet? How do the supra-thermal populations (both ions and electrons) evolve?

• What are the physical process whereby changes in sources affect the System III/IV modulations, radial transport rate, dawn/asymmetries?

• Can a direct causal connection be made between the specific nature of Io volcanic eruptions that might cause enhanced sources of plasma?

• How much plasma does Europa contribute to the magnetosphere?

• What is the spatial distribution of the production of plasma in the three regions of the torus? Where is the separation between outward and inward transport? What is the nature and role of the torus ribbon region?

• What processes drive and control the radial transport rate? How do these processes vary with radial distance and (if at all) with plasma production rate?

**Extended Neutral Nebulae.** The only nebula that has been detected directly is that of sodium from Io. But it is clear that charge-exchange reactions must be generating clouds of Energetic Neutral Atoms – and perhaps even molecules. Specific open questions are:

• What are the fluxes of different neutral species (composition, energy, direction) out of the jovian system? Are these neutrals re-ionized? Where? And what is their fate?

• What are the fluxes of different neutral species (composition, energy, direction) inwards towards Jupiter and impacting the planet’s atmosphere? Are these neutrals re-ionized? Where? And what is their fate?

These components of the Io-Europa space environment are clearly highly coupled. While there are modulations and temporal variations, such changes seem to be limited to factors of a few (rather than wild swings of orders of magnitude). Thus, there must be both negative and positive feedback systems. Full understanding of this complex system will require both
comprehensive observations as well as systematic modeling – of each component separately as well as carefully coupled – to explore what factors control (qualitatively and quantitatively) the different components. The beauty of the Io-Europa system, however, is that the timescales for the different processes make the components separable: plasma takes a minute or so to pass each moon, neutrals survive ~hours orbiting Jupiter, and plasma moves through the magnetosphere over many days. This separation of time scales allows us to study each component independently and then couple them together.

7.2 Future Observations

The Juno mission is currently approaching the end of its primary mission, mapping out the polar regions as well as outer to middle magnetosphere (for review of magnetospheric science see Bagenal et al. 2017b; for updated orbits see Bolton et al. 2017a). As the line of apsides of the orbit precesses southward, the spacecraft crosses the jovigraphic equator closer to the planet. By the end of the primary mission (34 orbits, spring 2021) Juno reaches between the orbits of Ganymede and Europa. Moreover, the tilted magnetic field allows the spacecraft to cross magnetic fluxshells intersecting Europa’s and Io’s orbits and sample the torus. Should the Juno mission be continued beyond orbit 34, the spacecraft will directly pass through the Io plasma torus many times, as well as likely intersect the Alfvén wings that stretches downstream of Europa as well as Io (Figure 5).

While Juno in situ measurements of particles and fields are very valuable, it is key that the torus emissions are also monitored from the ground (Schmidt et al. 2018; Morgenthaler et al. 2019) and from the Hisaki satellite (Yoshikawa et al. 2014). Ground-based telescopes seem to be ever expanding in wavelength and aperture. Io’s volcanism is monitored in the IR but perhaps the extension into the millimeter range of telescope systems such as Atacama Large Millimeter Array are allowing detection of the molecular species (SO₂, SO, O₂, NaCl, KCl, S₂, etc. for Io; OH, H₂O for Europa). The James Webb Space Telescope will also provide valuable information in the IR with high resolution and sensitivity that may provide the temperature and behavior of erupting lavas, plus changes in the SO₂ atmosphere at Io (Keszthelyi et al. 2016). In the meantime, we urge the community to support semi-continuous monitoring of the more observable species (Na, K, S, S⁺, O, O⁺…) with modest-sized telescopes.

Looking farther to the future, the development of ESA’s JUICE and NASA’s Europa Clipper missions promise close exploration of the Europa system with perhaps some forays closer to Io. But to properly address the key scientific questions of Io’s peculiar role in the jovian system we need a mission that makes multiple close flybys of Io.

Acknowledgments

We are grateful to our colleagues who have assisted us in pulling this review together and gave us feedback on earlier drafts: Tim Cassidy, Thomas Kim, Ryoichi Koga, Peter Kollmann, Barry Mauk, Quentin Nenon, Apurva Oza, Chris Paranicas, Joachim Saur, Carl Schmidt, Nick Schneider, Todd Smith, Jamey Szalay, Nick Thomas, Kazuo Yoshioka. V. Dols is grateful to D. Strobel for providing the electron energy degradation rates used in the chemistry simulations of Io’s interaction. We thank Crusher Bartlett for support with graphics. We also thank Michael Mendillo and Kurt Retherford for exceedingly useful reviews. All previously published figures and data are cited with the only new data shown in the paper are in figures 7, 9 and 11 which are
available via DOI: 10.25810/28er-bv62. This research has been partially supported by the NASA-Outer Planet Research Grant NNX14AO37G. This work was supported at the University of Colorado as a part NASA's Juno mission supported by NASA through contract 699050X with the Southwest Research Institute.

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Figure 1. The Io-Europa Space Environment. The system comprises at least 10 components that span from the moons in to Jupiter and out into the interplanetary medium. Note that Io and Europa orbit Jupiter at 5.9 and 9.4 Rj where 1 Rj=radius of Jupiter = 71,494 km. (Credit: top – John Spencer, SwRI; bottom – Steve Bartlett)

Figure 2. Io and Europa Bulk Properties.

Figure 3. Io and Europa Surface Properties

Figure 4. Io and Europa Atmospheric Properties. a: Eruption of Tvashtar Patera imaged by New Horizons' LORRI imager 2007; b: HST SO2 absorption image by Feaga et al. (2009); c, d: daytime column density of SO2: Feaga et al. (2009); e: Galileo visible image of aurora and volcanic emissions Geissler et al. (2001); f: scale of atmosphere: equatorial exobase ~400km; g, h, HST images (HI 121.6 nm) from Roth et al. (2014a) i, j: HST images (OI 135.6 nm) from Roth et al. (2016); k: Cartoon of plume (NASA/ESA/SwRI); l: scale of atmosphere: exobase ~100 km.

Figure 5. Plasma-Io Electrodynamic Interaction. a, b: schematic of interaction between the surrounding plasma and Io (from Schneider & Bagenal 2007). c: Hubble Space Telescope image of Jupiter's UV aurora (Clarke et al. 2002) showing auroral footprints of Io, Europa and Ganymede. d: Pattern of Alfwen waves generated by Io, bounding between hemispheres of
Jupiter where bursts of radio emission are generated above the ionosphere (Gurnett & Goertz 1981).

**Figure 6.** Sketch of the concept of the multi-species chemistry approach of the local interaction at Io. A parcel of plasma of prescribed composition and energy is carried by the prescribed plasma flow into the atmosphere of Io. The ion-electron-neutral processes change the composition and energy of the plasma in the parcel, which are then collected along a specific GLL flyby of Io (here the J0 flyby in red) and compared to the observations. Such simulations aim at constraining the atmospheric distribution and composition of Io’s atmosphere. From Dols et al. (2012).

**Figure 7.** Plasma-atmosphere interaction at Io. Plasma properties at Io from a multi-species chemistry approach of the atmosphere-plasma interaction sketched in Figure 6. The plasma flow is prescribed as an incompressible flow around a conducting ionosphere, which is assumed to extend to 1.26 RIo (see text). From upper left in clockwise direction: the prescribed SO2 neutral density of the corona; the plasma flow slowed upstream and downstream and accelerated on the flanks; the resulting average ion temperature, which increases where SO2+ ions are picked up by a fast flow; the electron density resulting from the torus thermal electron ionization; the electron temperature, which decreases in the molecular atmosphere because of the efficient molecular cooling processes; and the resulting SO2+ density. These simulations do not include the ionization caused by the parallel electron beams detected in the wake of Io and nor do they include a day-night asymmetry of the SO2 atmosphere.

**Figure 8.** Net Production at Io. Estimate of the contribution of each plasma-neutral process above an exobase (at 150km altitude) using the multi-species modeling approach described in Figure 6. These calculations use a prescribed MHD flow different from the flow shown in Figure 7. Although these rates depend on the flow and the atmosphere prescribed, they provide a reasonable estimate of the relative contribution of each process. Photoionization likely contributes 10-15% of the total ionization (Saur et al. 1999). The most important loss processes are the SO2 electron-impact dissociation, which provide slow atomic neutrals (which are actually prescribed in our chemistry simulations) and a cascade of SO2 resonant charge-exchange reactions, which provide faster neutrals depending where they occur.

**Figure 9.** Plasma-atmosphere interaction at Europa. Plasma properties at Europa from a multi-species chemistry approach of the atmosphere-plasma interaction sketched in Figure 6. The plasma properties can be compared to Io’s in Figure 7. The flow is similar while O2 is the main atmospheric component and O2+ the main ion. As Europa’s atmosphere is more tenuous than Io’s, the interaction is weaker and the plasma properties do not vary as strongly as at Io.

**Figure 10.** Net Reactions at Europa. Estimate of the contribution of each plasma-neutral O2 process above an exobase at 70 km altitude. The plasma-neutral processes on H2 are not a significant loss of H2 and are not shown here. Although the rates vary with the prescribed flow and neutral distribution, they are much lower than the rates at Io shown in Figure 8.
Photoionization likely contributes 10-15% of the total ionization (Saur et al. 1998). Europa does not provide much plasma to the magnetosphere of Jupiter.

**Figure 11.** Densities of the plasma downstream of the interactions with (above) Io based on Dols et al. (2008, 2012) and (below) Europa based on Dols et al. (2016). To emphasize the comparison between Io and Europa’s composition, we plot the simulated composition of the plasma along a trajectory similar to the J0 Galileo inbound flyby of Io (Dols et al. 2008), downstream of the moon, close to the equatorial plane with a closest approach distance $\sim 0.5 \text{ R}_{\text{Eu}}$.

**Figure 12.** Neutral Clouds of Io (based on Wilson et al. 2002). Left - Io's sodium cloud on three spatial scales, as imaged by ground-based observations of sodium D-line emission (the bottom image is from Burger et al. 1999). The features observed on the left are explained by the three atmospheric escape processes shown schematically on the right.

**Figure 13.** Io (left) and Europa (right) neutral clouds as modeled by Smith et al. (2019). The color contours show local densities ($\text{cm}^{-3}$) in the XY plane ($-Y$ axis points toward the Sun). Bottom left is the vertically-integrated column density along the $Y=0$ axis in the equatorial plane.

**Figure 14.** Three regions of the Io plasma torus: Cold disk, ribbon, warm torus. (a) This computed image shows optical $S^+$ emission (b) EUV $S^{++}$ emission. 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 torus ansa 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. (c) net emission across the EUV spectrum as observed by Cassini UVIS. (d) Cartoon showing the three regions. The structure of the torus can exhibit strong longitudinal variations, and the relative brightnesses of different regions can vary with time.

**Figure 15.** Models of the Io plasma torus. Top: two-dimensional model of the electron density based on Voyager in situ measurements and distribution along field lines under diffusive equilibrium. Bottom: Cassini UVIS observations and physical chemistry models constrain torus composition (Based on Nerney et al. 2017).

**Figure 16.** Flow of (a) particles and (b) energy through the Io Plasma Torus, applying the physical chemistry model of Delamere & Bagenal 2003 for typical torus conditions. High charge-exchange rates (McGrath & Johnson 1989) cause about half of the material (primarily O) to be lost from the system as fast neutrals, while the remainder is transported out as plasma. Most of the energy is radiated away via UV emissions. Input of energy from hot electrons is key for maintaining the torus. (Based on Nerney & Bagenal 2020).

**Figure 17.** (a) Ground-based observations of $S^+$ emissions from the torus (based on Schneider & Trauger 1995). While $S^+$ is a minor constituent of the warm outer torus it dominates the ribbon and the cold inner torus. (b) Voyager PLS measurement of ion species in the cold inner torus. (c) Herbert et al. (2008) re-analyzed observations by Schneider & Trauger (1995) of the cold torus to derive the 3-D distribution of $S^+$ density shown in (d). The red and green lines in (c) are the
centrifugal and magnetic equators derived from the JRM09+CAN magnetic field model of Connerney et al. (2018). From Herbert et al. (2008) and Bagenal et al. (2017).

**Figure 18.** Top – equatorial plasma density of electrons and main ion constituents (based on *Voyager* data presented by Dougherty et al. 2017). Mass-discriminated density of energetic (~100 keV) ions (middle) and fluxes of oxygen ions for different energies (bottom) measured by the *Galileo* EPD instrument (Allen et al. 2019).

**Figure 19.** Europa Neutral Cloud as observed by Cassini's MIMI instrument (Krimigis et al. 2002; Mauk et al. 2004) via very Energetic Neutral Atoms (H, O) at energies of ~100 keV.

**Figure 20.** Side view of the jovian system (brown arrow shows Jupiter's spin axis). Nebulae of very Energetic Neutral Atoms (spherical, based on Krimigis et al. 2002) and lower Energetic Neutral Atoms in the equatorial Mendillo-disk. Inserted bottom right is a histogram of counts versus mass/charge summed over days 338-362, 2000, before the Cassini bow shock encounter. Major peaks are identified on the plot but counts have not been normalized, so no relative elemental abundances are implied (Krimigis et al. 2002).
<table>
<thead>
<tr>
<th>Atmospheric Property</th>
<th>Io</th>
<th>Europa</th>
</tr>
</thead>
</table>
| Source (1)           | - SO₂ sublimation in daylight hemisphere.  
- Volcanoes at night?  
- Surface sputtering negligible | - Sputtering by thermal, high energy ions (2)  
- Pick-up ions? (3)  
- Plumes? (4)  
- Sub-solar source? (5) |
| Asymmetry (1, 6)     | - Day/night  
- Upstream/downstream  
- Pole/equator<35 deg  
- Jovian/anti-jovian | - Upstream/downstream  
- Jovian/anti-jovian?  
- Day/night? |
| Composition - detected (6, 7, 10) | SO₂, O, S, SO NaCl, KCl | O₂, O, H, H₂O |
| Composition - expected | O₂ | H₂ |
| Surface pressure (8, 6) | ~ 2 nbar SO₂ | ~ 200 pbar O₂ |
| Column density (9, 10) | [15-150] x 10^{15} cm⁻² | [0.2-2] x 10^{15} cm⁻² |
| Ionosphere peak density (11, 6) | 28 x 10⁴ cm⁻³ at 80 km | 1.3 x 10⁴ cm⁻³ at 50 km |
| Time variability | - With distance from Sun (12)  
- With volcanic activity? (13) | - Plume activity? (4)  
- Dawn-Dusk (14) |

<table>
<thead>
<tr>
<th>Property Upstream of Satellite</th>
<th>Io</th>
<th>Europa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range from magnetic equator</td>
<td>±1 R_J</td>
<td>±1.5 R_J</td>
</tr>
<tr>
<td>Range from centrifugal equator</td>
<td>±0.65 R_J</td>
<td>±1 R_J</td>
</tr>
<tr>
<td>Local jovian magnetic field</td>
<td>1720–2080 nT</td>
<td>420–480 nT</td>
</tr>
<tr>
<td>Plasma-moon relative velocity</td>
<td>53–57 km/s</td>
<td>65–110 km/s</td>
</tr>
<tr>
<td>Electron density</td>
<td>1200–3800 cm⁻³</td>
<td>65–290 cm⁻³</td>
</tr>
<tr>
<td>Alfven Mach number</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>plasma sheet center</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal electron temperature</td>
<td>5 eV</td>
<td>10–30 eV</td>
</tr>
<tr>
<td>Hot electrons</td>
<td>0.2% at 40 eV</td>
<td>2–10% at 250 eV</td>
</tr>
<tr>
<td>Major ions</td>
<td>S⁺⁺ (20%) O⁺ (25%)</td>
<td>S⁺⁺ (20%) O⁺ (20%)</td>
</tr>
<tr>
<td>Average Ion temperature</td>
<td>20–90 eV</td>
<td>50–500 eV</td>
</tr>
<tr>
<td>Average ion gyroradius</td>
<td>~3 km</td>
<td>~10 km</td>
</tr>
</tbody>
</table>

Table 2. Plasma conditions upstream of Io and Europa. (Based on Kivelson et al. 2004; Bagenal et al. 2015)
<table>
<thead>
<tr>
<th>Plasma-Atmosphere</th>
<th>Io</th>
<th>Europa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galileo flybys</td>
<td>J0, I24, I27, I31, I32</td>
<td>E4, E6, E11, E12, E14, E15, E16, E17, E19, E26</td>
</tr>
<tr>
<td>Flow diversion</td>
<td>95 % (1)</td>
<td>60 - 80 % (23, 2)</td>
</tr>
<tr>
<td>Magnetic perturbation</td>
<td>700 nT (3)</td>
<td>80 nT (4, 23)</td>
</tr>
<tr>
<td>Main ion-neutral process</td>
<td>Collision and chex (1, 5)</td>
<td>Collisions and chex (2, 6)</td>
</tr>
<tr>
<td>Ionization</td>
<td>• Thermal electron impact (3, 5)</td>
<td>• Thermal and hot electron impact (2, 6)</td>
</tr>
<tr>
<td>Main ion produced</td>
<td>SO$_2^+$ ~200 kg/s (1, 5, 8)</td>
<td>O$_2^+$ ~20 kg/s (2, 6)</td>
</tr>
<tr>
<td>Wake</td>
<td>N$_e$<del>30,000 cm$^{-3}$ slow flow (</del> 1 km/s) cold ions (~ 1 eV) (8, 9)</td>
<td>No clear plasma wake at Galileo altitude? (10)</td>
</tr>
<tr>
<td>Auroral emissions</td>
<td>Mainly O (11) also S (12), Na, K (13)</td>
<td>Mainly O also H Lyman-alpha (14)</td>
</tr>
<tr>
<td>Aurora location</td>
<td>• Equatorial flanks (15)</td>
<td>• Polar emissions stronger on side of plasma sheet (14)</td>
</tr>
<tr>
<td>Electron beams location</td>
<td>In wake J0, above poles (I31, I32) (17)</td>
<td>No beams detected by Galileo</td>
</tr>
<tr>
<td>Electron beams energy</td>
<td>• &gt;150 eV Powerlaw distribution (18)</td>
<td></td>
</tr>
<tr>
<td>Footprint emissions</td>
<td>Multi-spot structure + long tail (19)</td>
<td>Double-spot structure + short tail (20)</td>
</tr>
<tr>
<td>Induced mag field in subsurface</td>
<td>Yes (21)</td>
<td>No (22, 23)</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Sources &amp; Losses</th>
<th>Io</th>
<th>Europa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Loss processes (1, 2)</td>
<td>• Exospheric collisions, chex</td>
<td>• Jeans escape?</td>
</tr>
<tr>
<td></td>
<td>• Atmospheric sputtering</td>
<td>• Exospheric collision</td>
</tr>
<tr>
<td></td>
<td>• SO$_2$ electron impact</td>
<td>• O$_2$ electron impact</td>
</tr>
<tr>
<td></td>
<td>dissociation</td>
<td>dissociation</td>
</tr>
<tr>
<td></td>
<td>• Direct volcanic injection</td>
<td>• Direct plume injection</td>
</tr>
<tr>
<td></td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>• Surface sputtering negligible</td>
<td></td>
</tr>
<tr>
<td>Net Neutral loss (1, 2)</td>
<td>250 - 3000 kg/s</td>
<td>25 - 70 kg/s</td>
</tr>
<tr>
<td>Neutral clouds (3, 4) - detected</td>
<td>S, O, Na, K</td>
<td>H, O, Na, K</td>
</tr>
<tr>
<td>Neutral clouds - expected</td>
<td>SO$_2$, SO ?</td>
<td>H$_2$, O$_2$ ?</td>
</tr>
<tr>
<td>Sodium sources (5)</td>
<td>10 - 30 kg/s</td>
<td>??</td>
</tr>
<tr>
<td>Local plasma source (6, 7)</td>
<td>~200 kg/s</td>
<td>~20 kg/s</td>
</tr>
<tr>
<td>Extended plasma source (11)</td>
<td>700- 2000 kg/s</td>
<td>~60 kg/s</td>
</tr>
<tr>
<td></td>
<td>Cold Disk</td>
<td>Ribbon</td>
</tr>
<tr>
<td>------------------</td>
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<td>--------------</td>
</tr>
<tr>
<td>Location (R₉)</td>
<td>4.7 - 5.7</td>
<td>5.6 - 5.9 ?</td>
</tr>
<tr>
<td></td>
<td>Height 0.2</td>
<td>Width 0.2</td>
</tr>
<tr>
<td>Mass</td>
<td>35 kton</td>
<td>200 kton</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>10%</td>
</tr>
<tr>
<td>Radial Transport</td>
<td>Inward:</td>
<td>Outward:</td>
</tr>
<tr>
<td>(R₉)</td>
<td>months</td>
<td>20 - 60 days</td>
</tr>
<tr>
<td>Nₑ (cm⁻³)</td>
<td>~1000</td>
<td>~3000</td>
</tr>
<tr>
<td>Tₑ (eV)</td>
<td>&lt;2</td>
<td>~5</td>
</tr>
<tr>
<td>Hot Electrons</td>
<td>~0</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Tᵢ (eV)</td>
<td>&lt;2</td>
<td>20 - 40</td>
</tr>
<tr>
<td>Ions</td>
<td>S⁺, O⁺</td>
<td>O⁺, S⁺, S''⁺</td>
</tr>
</tbody>
</table>

**Table 5.** Plasma Torus Properties (see section 5).
## Io & Europa: Bulk & surface properties

<table>
<thead>
<tr>
<th></th>
<th>Io</th>
<th>Europa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Period</td>
<td>42.5 hours</td>
<td>85.2 hours</td>
</tr>
<tr>
<td>Semi-major axis</td>
<td>$5.90 \pm 0.024 \text{ R}_J$</td>
<td>$9.38 \pm 0.085 \text{ R}_J$</td>
</tr>
<tr>
<td>Radius</td>
<td>1822 km</td>
<td>1561 km</td>
</tr>
<tr>
<td>Mass</td>
<td>$8.93 \times 10^{22} \text{ kg}$</td>
<td>$4.80 \times 10^{22} \text{ kg}$</td>
</tr>
<tr>
<td>Density</td>
<td>3528 kg m$^{-3}$</td>
<td>3013 kg m$^{-3}$</td>
</tr>
<tr>
<td>Escape speed</td>
<td>2.6 km s$^{-1}$</td>
<td>2.0 km s$^{-1}$</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.62</td>
<td>0.64</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>110-1500 K</td>
<td>110-132 K</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>&gt;425 volcanic basins, ~250 active volcanoes, 50-100 erupting</td>
<td>Magnetic perturbations show liquid ocean under the ice</td>
<td></td>
</tr>
<tr>
<td>Global resurfacing ~1 cm / year. Craters removed in ~1 million years. Turns inside out 40 times in 4.5 Ga</td>
<td>Geophysical evidence ice 5-30 km. Geological features suggests thinner brittle layer over ductile ice.</td>
<td></td>
</tr>
<tr>
<td>Where/how are tides dissipated to drive volcanism?</td>
<td>How much contact between ocean and surface?</td>
<td></td>
</tr>
<tr>
<td>Io</td>
<td>Europa</td>
<td></td>
</tr>
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<tr>
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<td><img src="l" alt="Image" /></td>
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</tr>
</tbody>
</table>
a) Diagram showing plasma flow and current sheets.

b) Diagram illustrating exosphere, atmosphere, and radiation sources.

c) Image with Io, Europa, and Ganymede labeled.

d) Diagram indicating field-aligned currents and Io plasma torus.
Upstream: $n_{el}, n_i, T_{el}, T_i$
ions = $S^+, S^{++}, S^{+++}, O^+, O^{++}$

Prescribed neutral atmosphere:
$N_{S,O,SO,SO_2}(r, \theta, \varphi)$

Prescribed flow of the flux tube

Ionization
Charge exchange
Recombination

GLL trajectory: $n_{el}, n_i, T_{el}, T_i$
ions = $S^+, S^{++}, S^{+++}, O^+, O^{++}, SO_2^+, SO^+$
SO₂ → SO₂⁺

Flow velocity (km/s)

SO₂⁺ Density (cm⁻³)

ne

Electron density (cm⁻³)

Electron temperature (eV)

Ion Temperature (eV)
Io

Upstream (J0)
\[ N_{el} \approx 4000 \, \text{cm}^{-3} \]
\[ T_{el} = 5 \, \text{eV} \]
\[ T_{i} \approx 100 \, \text{eV} \]

**Impact-ionization**
\[ \text{SO}_2 + e^- \rightarrow \text{SO}_2^+ + 2e^- \]
105 kg/s

**Impact-dissociation**
\[ \text{SO}_2 + e^- \rightarrow \text{O} + \text{SO} \]
1,500 kg/s

**Asymmetric -chex with O^+**
\[ \text{S}^{++} + \text{SO}_2 \rightarrow \text{S}^+ + \text{SO}_2^+ \]
\[ \text{O}^+ + \text{SO}_2 \rightarrow \text{O} + \text{SO}_2^+ \]
30 kg/s

**SO\(_2\) Resonant-chex**
\[ \text{SO}_2^+ + \text{SO}_2 \rightarrow \text{SO}_2 + \text{SO}_2^+ \]
1,600 kg/s

**Recombination-Dissociation**
\[ \text{SO}_2^+ + e^- \rightarrow \text{O} + \text{SO} \]
Local = 10 kg/s
Far = 105 kg/sec

**SO\(_2\) elastic collision**
Induced dipole attraction
110 kg/s
Europa

Upstream
\( N_{el} \approx 158 \text{ cm}^{-3} \)
\( T_{el} = 20 \text{ eV} \)
\( T_1 \approx 88 \text{ eV} \)

Impact-ionization
\( O_2 + e^- \rightarrow O_2^+ + 2e^- \)
20 kg/s

Impact-dissociation
\( O_2 + e^- \rightarrow O + O \)
10 kg/s

Asymmetric -chex with O^+
\( S^{++} + O_2 \rightarrow S^+ + O_2^+ \)
\( O^+ + O_2 \rightarrow O + O_2^+ \)
1 kg/s

O_2 Resonant-chex
\( O_2^+ + O_2 \rightarrow O_2 + O_2^+ \)
40 kg/s

Recombination-Dissociation
\( O_2^+ + e^- \rightarrow O + O \)
Local = \( \leq 1 \text{ kg/s} \)
Far = 20 kg/sec

O_2 elastic collision
Induced dipole attraction
10 kg/s

\( N_{col O_2} = 5 \times 10^{14} \text{ cm}^{-2} \)
IO SODIUM CLOUDS

Schneider & Trauger

Burger et al. 1999

Jupiter

15 R_J

Stream

9 R_{lo}

Jet

Io's orbit

15 R_J
Warm Torus

S$^+$ at 6731Å

Cold Disk

S$^{++}$ at 685Å

UV emission

d

b

Ribbon

a
The electron density is determined at each iteration by the quasi-neutrality condition (assuming $n_{H^+}/n_e = 0.1$): $n_e = (n_{S^+} + 2n_{S^{++}} + 3n_{S^{+++}} + n_{O^+} + 2n_{O^{++}})/0.9$.
Energy Budget

Recombination
Ionization (thermal e⁻)
Ionization (hot e⁻)
Coulomb Collisions

Total radial transport = 3%  Total CHEX = 6%  Total radiated = 91%

100% = 0.66 (eV cm⁻³ s⁻¹)
Europa

Observed Energetic Neutral Atoms ~100 keV H, O
10s-100s keV - vENAs
Energetic ions charge exchange with Europa neutral cloud

100s eV - ENAs
Thermal ions charge exchange near Io

Solar Wind

Sun