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Key Points:
- An independent confirmation of the Europa neutral gas torus is provided based on never-reported energetic sulfur ion observations
- Protons and sulfur ions are likely to interact with two different neutral torii: a thin oxygen torus and a thick hydrogen one

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Evidence of Europa Neutral Gas Torii From Energetic Sulfur Ion Measurements

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Abstract Imaging of energetic neutral atoms coming from a trans-Europa region and energetic proton observations by Galileo around Jupiter have previously revealed the existence of a neutral gas torus produced by Europa. Energetic sulfur ions observed by Galileo do not show any effect of the Europa torus for Mc Ilwain parameters $L > 9.2$, surely because ions are multiply charged, so that the torus first needs to bring the ions charge state to one before being able to neutralize them. Signatures of the Europa torus in energetic sulfur ion measurements obtained near the magnetic equator at $L = 9.08$–9.20 during Galileo orbits C10 and E11 are reported for the first time in this letter. They provide an independent confirmation of the Europa neutral gas torus. Pitch angle distributions suggest that protons might principally interact with a vertically thin neutral oxygen torus, while sulfur ions are lost by charge exchange with a vertically thicker hydrogen torus.

Plain Language Summary The icy moon Europa around Jupiter creates a large cloud of neutral particles in space that has not been observed in situ so far. Observation of this cloud is only possible through the effect it has on energetic positively charged ions, like protons or heavier ions. Previous observations have proved the existence of the Europa neutral gas torus by looking at the protons, as the interaction with the torus simultaneously removes the protons and creates energetic neutral particles. In this article, we show never-reported-before depletions of the sulfur ion fluxes measured by the Galileo spacecraft that independently confirm the existence of the neutral torus. In addition, comparing the sulfur ions and protons measurements, we find that the molecular hydrogen torus is likely to be vertically thicker than the oxygen torus.

1. Introduction

The volcanic moon Io and the icy moon Europa orbit at around 5.9 Rj and 9.3 Rj from the center of Jupiter (1 Rj = 71,492 km) and are at the origin of neutral gas clouds, also named *neutral gas torii*. The torii extend not only near the orbits of the moons but are spread in most of the inner magnetosphere of Jupiter (Smith et al., 2019). Interaction of charged particles of the Jovian plasma with the neutral particles and atoms of the torii is so far the only mean to confirm their existence and study their properties and possible time dynamics.

Indeed, excitation of neutral sodium and oxygen particles of the Io torus by cold plasma electrons and solar photons lead to observable ultraviolet emissions (Koga et al., 2018). No ultraviolet emission has been detected coming from the Europa neutral torus (Hansen et al., 2005).

Charge exchange reactions between energetic ions trapped in the radiation belts of Jupiter and neutral gas torii particles also enable to study the torii. Indeed, charge exchange of singly charged ions with the neutral material leads the ion to become neutralized and a so-called Energetic Neutral Atom (ENA). Charge exchange is therefore a source of ENAs and a loss process for energetic ions.

Smith et al. (2019) have shown that energetic ions mainly charge exchange with neutral particles and not with cold plasma ions, so that charge exchange signatures detected in ENA images or energetic ion measurements are linked to neutral torii.

Lagg et al. (1998) and Mauk et al. (2004) have shown observable effects of the Io neutral torus in the energetic oxygen and sulfur ion measurements obtained by the Energetic Particle Detector (EPD) onboard Galileo.

Mauk et al. (2003) have detected ENAs coming from the Europa torus, while Lagg et al. (2003) and Kollmann et al. (2016) have reported on clear signatures of the Europa torus in the proton measurements obtained by EPD.

However, no signature of the Europa torus has been reported so far for the oxygen and sulfur ions observed by EPD. Low-energy total ion EPD measurement channels may show the removal effect of the Europa torus on heavy ions, but this is unsure since these channels do not discriminate between protons and heavier ions (Mauk et al., 2004). The nondetection of the Europa torus in heavy ion measurements is at a first glance surprising for two reasons: (1) Singly charged heavy ions have higher probabilities to become neutralized than protons, and (2) the Io neutral torus very effectively removes heavy ions while its neutral densities might be of the same order or even lower than Europa torus ones (Smith et al., 2019).

Lagg et al. (2003) remind that EPD heavy ion measurement channels observe all ion charge states together. It was therefore proposed that the heavy ions are multiply charged near the Europa torus, so that the torus would need a longer time than for the protons to neutralize the ions. Indeed, the distribution function observed by EPD is the sum of all the ion charge state distribution functions, and its temporal decrease under charge exchange is given by

$$\frac{1}{\sum_n f_S n+}\frac{\mathrm{d}}{\mathrm{d}t}\left[\sum_n f_S n+\right] = -\sigma_{10} v n \frac{f_S+}{\sum_n f_S n+}, \tag{1}$$

where $f_{S^{n+}}$ is the distribution function of S^{n+} ions in the position-momentum phase space; v, the speed of the energetic ions; σ_{10}, the total single capture charge transfer cross section of singly charged S^+ with neutral particles; and $\langle n \rangle$, the density of neutral particles seen by the ions on average during their bounce and drift motions around Jupiter.

One can see with equation (1) that as long as the singly charged ion fluxes are small compared to other charge states ions ($f_{S^+} < \sum_n f_{S^{n+}}$), the effect of charge exchange on the observed sum of distribution functions can remain negligible.

Clark et al. (2016) provide further support for the multiple charging hypothesis by studying injection events arrival times, what enabled the previous authors to point out that energetic oxygen charge states are evenly distributed between 1 and 2, while sulfur charge states are more between 2 and 3. Keeping in mind that the ions are radially transported inward, from large to close distances to Jupiter, the scenario that has since emerged is that (1) energetic heavy ions are multiply charged above the orbit of Europa, (2) the neutral torus of Europa decreases the charge state of the heavy ions slowly enough so that we do not see any signature in the EPD measurements but fast enough to have a charge state close to 1 near the Io neutral torus, and (3) the Io torus effectively removes the ions because they are mainly singly charged (Mauk et al., 2004).

Kollmann et al. (2016) have shown that Lagg et al. (2003) did not consider Galileo orbits that enable to observe ions with equatorial pitch angles higher than 70° (equatorial pitch angles can take values between 0° and 90° in our paper). However, this population with high equatorial pitch angles is of major importance for torii characterization, as the higher the equatorial pitch angles, the more pronounced is likely to be the gas torus effect because these ions see higher average neutral densities (Kollmann et al., 2016). New findings were reported by Kollmann et al. (2016) for the protons by considering Galileo crossings of the magnetic equator.

In this article, we report on the equatorial pitch angle distributions of sulfur ions observed close to the magnetic equator by Galileo. Section 2 of this letter introduces the data set and method that we use. Section 3 then describes observed sulfur ion pitch angle distributions and compares them to distributions of protons in the Europa torus and sulfur ions in the Io neutral torus. Finally, section 4 details the impact of our new findings on not only the study of energetic sulfur ions in the inner magnetosphere of Jupiter but also on the existence and properties of the Europa neutral gas torus.

2. Data Set and Method

In this article, we use measurements of energetic protons and sulfur ions obtained by the low-energy end of the Composition Measurement System (CMS) of Galileo-EPD (Williams et al., 1992). This system measures the time of flight of the charged particles and the total energy they deposit in a solid state detector, what

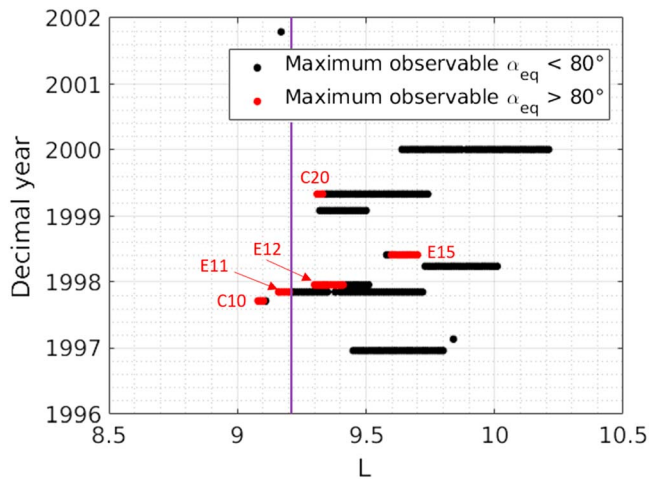

Figure 1. Decimal years and Mc Ilwain parameters of available unidirectional Energetic Particle Detector measurements in the Europa torus region. In red are highlighted the periods when Galileo was sufficiently close to the magnetic equator to be able to observe equatorial pitch angles higher than 80°. Orbit names are given in red only for these periods.

enables it to discriminate the mass of the charged particles. Four EPD-CMS measurement channels are studied hereafter and were already used in the Europa region by Lagg et al. (2003), Mauk et al. (2004), Clark et al. (2016), and Kollmann et al. (2016): TP1 (protons, 80–220 keV), TS1 (sulfur ions, 512–960 keV), TS2 (sulfur ions, 960–1,984 keV), and TS3 (sulfur ions, 1,984–9,920 keV).

Three kind of measurements are obtained by EPD:

1. eleven-minute averaged omnidirectional count rates, available during most of the Galileo mission;
2. count rates obtained every 1.25 s. The relatively narrow full opening angle of EPD-CMS of 18° and this high sampling rate enable to have quasi-unidirectional observations. Because the main antenna of Galileo did not deploy, the time coverage of these measurements is very sparse;
3. full record of the time of flight and total energy of particles, named *Pulse Height Analysis* (PHA) events.

PHA events have been used by Mauk et al. (2004) and Kollmann et al. (2016) to assess the data quality of EPD observations. They point out that the proton and sulfur ion measurements obtained by EPD-CMS are usable near Europa's orbit down to 7 Rj from the center of Jupiter until at least the orbit C23 of Galileo. In addition, the EPD-CMS low-energy end was frequently placed behind a shield to estimate the contamination from penetrating particles that is negligible against the foreground signals of the proton and sulfur channels we use here.

Omnidirectional count rates of TP1, TS1, TS2, and TS3 do not show any flux decrease near Europa's orbit (Paranicas et al., 2009), so that possible signatures of interactions with the Europa gas torus can only be seen in directional measurements, as already reported for the protons (Kollmann et al., 2016; Lagg et al., 2003).

In this paper, we use the unidirectional count rates obtained by EPD-CMS, that we convert to unidirectional differential fluxes with the geometric factors and energy passbands provided by Kollmann et al. (2018). Following Kollmann et al. (2016), we focus in this paper on particles coming from directions that have an angle with the plasma flow of at least 60°. Finally, following once again Kollmann et al. (2016), we do not use measurements obtained when the motor that rotates EPD was in position number 7.

The angle between the telescope viewing direction and the local magnetic field vector is retrieved from the Galileo magnetometers observations (Kivelson et al., 1992). The combination of the VIP4 internal magnetic field model of Jupiter (Connerney et al., 1998) with the external field model of Khurana and Schwarzl (2005) is used to map local pitch angles to equatorial pitch angles. We use the IDL routine available online at http://lasp.colorado.edu/mop/resources/. In this paper, the Mc Ilwain parameter L is the distance between the position of the magnetic field amplitude minimum on the field line (computed with the previous complex magnetic field model) and the center of the Jovian dipole. The dipole center coordinates given in the System III right-handed system frame are, according to the VIP4 model, (−0.093, 0.053, and −0.001) Rj.

We restrict our analysis to instances when simultaneously the EPD high-sampling acquisition mode was turned on to observe directional count rates and Galileo was sufficiently close to the magnetic equator to observe equatorial pitch angles $\alpha_{eq} > 80^{\circ}$. Figure 1 shows that it let us with five narrow time periods with $8.5 < L < 11$, three of which have $L > 9.2$ during orbits E12, E15, and C20, and two with $L < 9.2$, during orbits C10 and E11. Table 1 gives the considered time intervals and L ranges used in this study that are smaller than the ones shown on Figure 1 for the Europa flyby orbits (E11, E12, and E15) in order to exclude local effects of the moon. One can see that the considered L intervals for each orbit are very small, in fact small enough so that pitch angle distributions reported hereafter do not show the L gradient of the ion distribution but actually shows its anisotropy.

Table 1
Time Intervals Considered in This Study

Orbit	Time period	Mc Ilwain parameter L	Maximum observable equatorial pitch angle
E15	31 May 1998 21:24:38–21:41:35 Europa CA at 21:12:57	9.579–9.598 $L_{CA} = 9.617$	82°
E12	16 December 1997 12:15:21 s-12:27:03 Europa CA at 12:03:20	9.436–9.508 $L_{CA} = 9.377$	83°
C20	03 May 1999 17:33:51–17:59:10	9.309–9.348	85°
E11	06 November 1997 22:25:34–22:49:47 Europa CA at 20:31:44 s	9.160–9.181 $L_{CA} = 9.601$	89°
C10	18 September 1997 22:34:54 s-23:19:27	9.079–9.106	89°

Note. In the orbit names, the first letter indicates the orbit objective, "E" for Europa or "C" for Callisto, and the digits give the orbit number out of 35. For Europa flyby trajectories, the date and Mc Ilwain parameter of closest approach (CA) to Europa are indicated. The maximum observable equatorial pitch angle only depends on the magnetic latitude of the spacecraft and is given by $\mathrm{asin}\left(\sqrt{\frac{B_{\mathrm{eq}}}{B_{\mathrm{local}}}}\right)$, where B_{local} is the local magnetic field strength, and B_{eq} is the equatorial field amplitude.

3. Observations

Figure 2A shows the sulfur ion pitch angle distribution already reported by Lagg et al. (1998) in the Io neutral gas torus at $L = 6.41$–6.50 during orbit I0. Unidirectional fluxes of the sulfur ions in the Io torus increase from $\alpha_{\mathrm{eq}} = 0^{\circ}$ to $\alpha_{\mathrm{eq}} = 35^{\circ}$ and then decrease with increasing pitch angles. This has been interpreted as the fact that the low pitch angle ions have a trapped distribution (also named *pancake*) that has not yet been affected by the interaction with the neutral gas (Lagg et al., 1998). Higher equatorial pitch angle ions see an average neutral density during their bounce and drift motion that is larger than the low equatorial pitch angle ions (see for instance Figure 2 of Kollmann et al., 2016), what explains the decreasing pattern observed for $\alpha_{\mathrm{eq}} > 35^{\circ}$.

Figure 2B shows the pitch angle distribution of 130-keV protons during orbit C20 in the Europa torus, already reported by Kollmann et al. (2016). Fluxes are continuously decreasing with increasing pitch angles from $\alpha_{\mathrm{eq}} = 25^{\circ}$, so most of the equatorial pitch angle protons have already been depleted by charge exchange with the Europa torus. The increase seen for $\alpha_{\mathrm{eq}} > 70^{\circ}$ has been interpreted by Kollmann et al. (2016) as an evidence that the Europa torus is thin enough so that equatorial protons with $\alpha_{\mathrm{eq}} \approx 90^{\circ}$ bounce most of their time below and above the torus, because of the 9.5° Jovian magnetic field tilt. Equatorial protons therefore see an average neutral density lower than $\alpha_{\mathrm{eq}} = 70^{\circ}$ protons.

Figure 2C shows the unidirectional fluxes observed by the three sulfur channels TS1, TS2, and TS3 during the five time intervals of interest. The measured flux intensities continuously increase from low pitch angles to higher pitch angles for the three orbits E12, E15, and C20, with $L > 9.31$. These pancake distributions tend to show that the particles have not yet reached a single state charge that would enable them to be depleted by charge exchange with the Europa torus.

During orbit E11 at $L = 9.16$–9.17, fluxes of sulfur ions with equatorial pitch angles higher than 80° (in red on Figure 2C) decrease with increasing pitch angles for TS1 and TS2 but not for TS3. The decrease is stronger closer to Jupiter during orbit C10 at $L = 9.08$–9.11, with a decrease of 20% for TS1 and 15% for TS2, while TS3 keeps a pancake distribution. For comparison, the flux increase reported by Kollmann et al. (2016) for $\alpha_{\mathrm{eq}} > 70^{\circ}$ protons is about 17%.

By analogy with the Io neutral torus, energetic oxygen ion depletions should be less pronounced than sulfur ion depletions (Lagg et al., 1998). EPD oxygen ion measurements in the Europa torus have larger standard deviations than sulfur ion ones, so that the instrument performances do not enable to detect the Europa torus effect in the oxygen channels with a good confidence level.

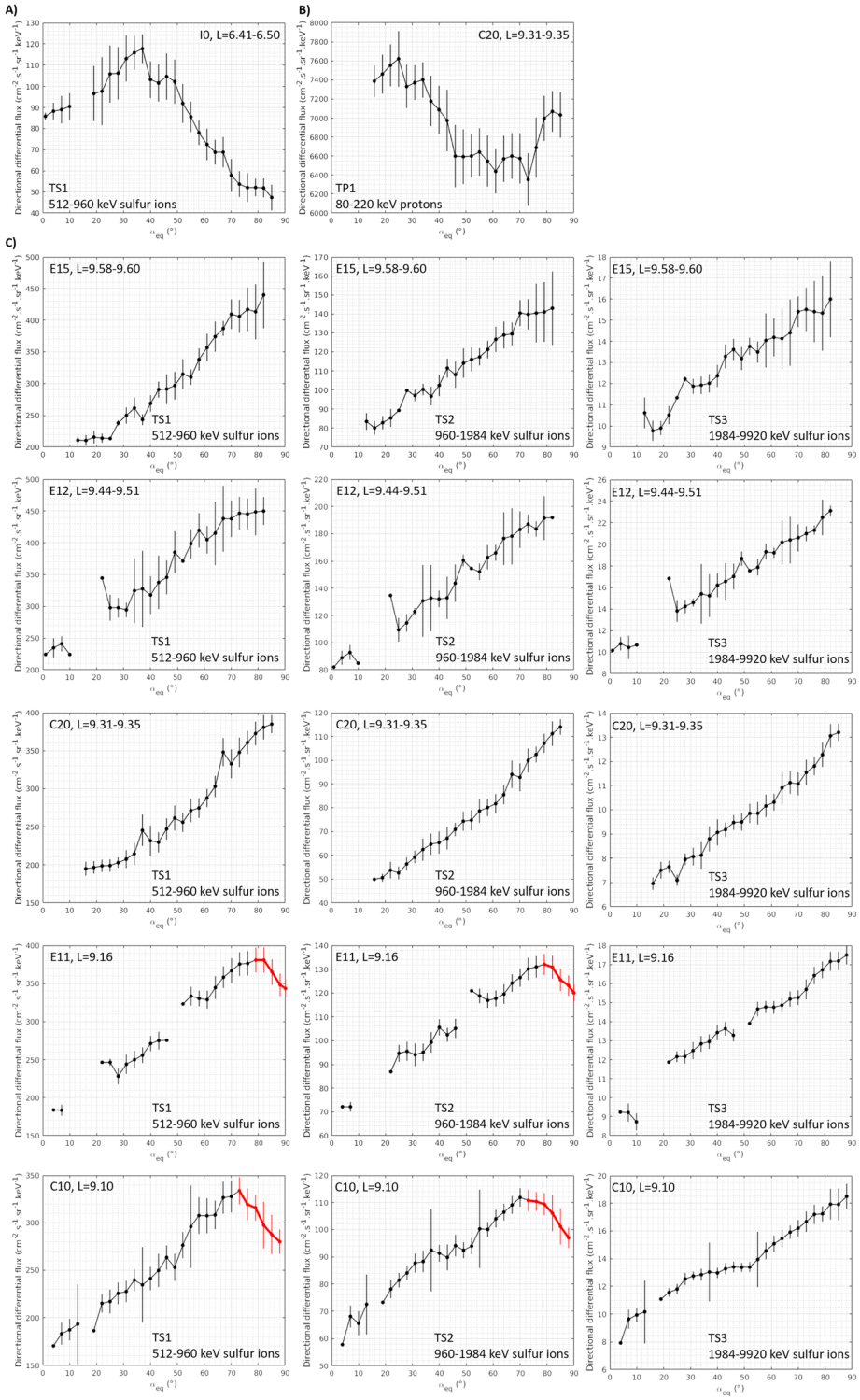

Figure 2. (A) Equatorial pitch angle distributions observed by the measurement channel TS2 of the Energetic Particle Detector (960- to 1,984-keV sulfur ions) in the Io torus region during orbit I0 in December 1995. Equatorial pitch angles α_{eq} are given for the center of the viewing cone of EPD-CMS. The points show the data median computed within a 4° wide pitch angle interval, and the error bars show the 1σ standard deviation. (B) Equatorial pitch angle distributions observed by the channel TP1 (80- to 220-keV protons) in the Europa torus during the time interval of orbit C20 given in Table 1. (C) Equatorial pitch angle distributions observed by the sulfur ion channels in the Europa torus region. Times intervals used for each orbit are detailed in Table 1. The flux decreases highlighted in red show the observable effect of the Europa neutral gas torus on energetic sulfur ions.

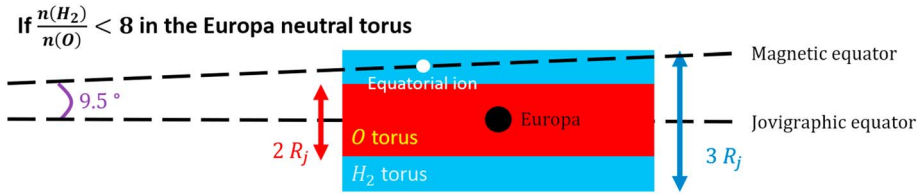

Figure 3. A sketch showing a possible scenario to explain energetic protons and sulfur ions interactions with two different Europa gas torii: Protons are mainly lost by charge exchange with a thin oxygen torus, so that equatorial protons see a lower average neutral density than $\alpha_{eq} = 70^{\circ}$ protons. Sulfur ions primarily interact with a vertically thicker molecular hydrogen torus.

4. Interpretation and Conclusions

We do not see any evidence of an effect of the Europa torus on the sulfur ions for $L > 9.3$, what can be because the orbit of Galileo did not enable to observe $\alpha_{eq} > 85^{\circ}$ ions there or because the Europa torus removal effect is not effective yet, as the ions are still mainly multiply charged (Clark et al., 2016).

The fact that the high-energy channel TS3 do not show the flux decrease observed in the lower energy channels TS1 and TS2 tends to dismiss moon absorption as an explanation of the reported flux decrease for $L < 9.2$. It is similar to the protons observed by TP1 (low energy) and TP2 and TP3 (higher energies; Kollmann et al., 2016). In addition, moon absorption is more effective for equatorial pitch angles of around 70° and negligible for $\approx 90^{\circ}$ ions, as equatorial ions cross the moon orbital plane only twice during their drift motion. The fact that TS3 does not show the same behavior as TS1 and TS2 favors charge exchange as the origin of the observed ion depletions, as charge exchange probabilities decrease with increasing kinetic energies (Ozak et al., 2010; Sakabe & Izawa, 1991).

Pitch angle scattering by wave-particle interaction moves high pitch angle ions to lower pitch angles if the distribution is initially a pancake, until they reach the loss cone. The pancake distribution observed for $L > 9.3$ should therefore remain peaked at 90° if mainly affected by wave-particle interaction, what is not observed.

Finally, the equatorial pitch angle of the flux maximum is of around 80° at $L = 9.16$ and 70° at $L = 9.10$. The shift toward lower pitch angles with decreasing L is consistent with losses by charge exchange with the neutral torus. Indeed, the low pitch angle ion fluxes are depleted after the higher pitch angle ones (or more inward, as ions are transported inward). We therefore reach the same conclusion as Lagg et al. (1998) for the Io torus, but regarding the Europa torus: energetic sulfur ions are lost by charge exchange with neutrals.

The signatures reported for $L < 9.2$ during orbits C10 and E11 show that charge exchange is effective enough in the Europa torus to bring the charge state of $\alpha_{eq} > 70^{\circ}$ sulfur ions close to 1 and deplete this population. Lower equatorial pitch angle ions are likely to have a charge state that decreases toward 1 latter on when transported closer to Jupiter. The decrease of the charge state by charge exchange with the Europa torus explains why the sulfur ions are quickly removed by the Io neutral torus (Mauk et al., 2004). Pitch angle distributions reported in this letter therefore confirm the coupling between the Io and Europa torus in shaping energetic heavy ions distributions around Jupiter.

The pitch angle distribution shape at high equatorial pitch angles, with decreasing fluxes, tends to show that the Europa torus is large enough so that equatorial ions spend more time in the neutral torus than 70° ions. It requires a torus with a full thickness of (see Figure 3):

$$H = 2\,\rho \tan(\theta_{MAG}) \approx 3\,R_j, \tag{2}$$

where H is the full thickness of the torus, ρ is the equatorial distance of the torus from Jupiter's dipole center, $\rho = 9\ R_j$, and θ_{MAG} is the tilt of the Jovian magnetic field axis with respect to the rotation axis of the planet, $\theta_{MAG} \approx 9.5^{\circ}$.

In order to explain the sulfur ion observations, we therefore find that the full thickness of the Europa neutral torus should be of at least 3 Rj, what is inconsistent with what has been proposed from proton observations by Kollmann et al. (2016), as the full thickness should be lower than 2 Rj.

A possible explanation of this inconsistency is that the energetic protons do not charge exchange with the same specie as the energetic sulfur ions. We further explore this hypothesis hereafter by considering charge exchange reactions of protons and sulfur ions with molecular hydrogen H_2 and atomic oxygen O. The two previous neutral species are likely to dominate neutral particle number densities in the Europa gas torus (Smith et al., 2019).

The ratio of the charge exchange cross sections of S^+ ions with neutral S and H_2 is lower than 1.5 for the kinetic energies observed by TS1 and TS2 (Ozak et al., 2010; Sakabe & Izawa, 1991). As resonant charge exchange between S^+ and neutral S is more effective than S^+ on neutral oxygen O (McGrath & Johnson, 1989), we have

$$\frac{\sigma_{10}(S^+ + O)}{\sigma_{10}(S^+ + H_2)} < 1.5,$$

where $\sigma_{10}(S^+ + O)$ is the total single capture charge transfer cross section of S^+ ions with neutral oxygen and $\sigma_{10}(S^+ + H_2)$ is its counterpart for molecular hydrogen.

H_2 densities in the Europa torus are likely larger than neutral oxygen ones (Smith et al., 2019), so that energetic sulfur ions are principally lost by interaction with molecular hydrogen.

The charge exchange ratio for 130-keV protons is (Barnett et al., 1990; Paranicas et al., 2008)

$$\frac{\sigma_{10}(H^+ + O)}{\sigma_{10}(H^+ + H_2)} \approx 8.$$

So, if the ratio $\frac{n(H_2)}{n(O)}$ is lower than 8, protons mainly interact with neutral oxygen. The neutral gas torus model of Smith et al. (2019) shows that it is possible, since the previous density ratio is reported by their model to be of around 3 to 5 for most of the longitudes. In addition, the oxygen source rate imposed near Europa by Smith et al. (2019) may be underestimated (Smith et al., 2019).

Based on available cross sections, if the ratio $\frac{n(H_2)}{n(O)}$ is lower than 8, we end with the scenario shown by the sketch of Figure 3, in which energetic protons might be lost principally by charge exchange with a thin oxygen torus, while energetic sulfur ions are lost by interactions with a vertically thicker molecular hydrogen torus. The model of Smith et al. (2019) confirms that the H_2 torus is vertically thicker than the O torus (see their Figures 4 and 5).

Juno will fly in the Europa torus region close to the magnetic equator during and after its 23rd orbit in November 2019. The Juno-Jupiter Energetic particle Detector Instrument (Mauk et al., 2017) observes energetic ions and can be used to further discuss the findings reported in this letter. Major breakthroughs will come from the Jovian Energetic Neutral and Ions instrument of the Plasma Environment Package (PEP) onboard the ESA JUICE mission (Grasset et al., 2013) that will arrive in orbit around Jupiter in late 2029.

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