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Key Points:

- The average lifetimes of energetic protons and electrons due to moon absorption vary dramatically from ~0.1 to well above 1,000 days
- Considering the moons as insulators, we find that the absorption of energetic protons and electrons by Io is the most intense
- Average proton lifetimes are longer than electron lifetimes at energies below a few MeV but shorter at energies above tens of MeV

Supporting Information:

Supporting Information may be found in the online version of this article.

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Losses of Radiation Belt Energetic Particles by Encounters With Four of the Inner Moons of Jupiter

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Abstract Based on an improved model of the moon absorption of Jovian radiation belt particles, we investigate quantitatively and comprehensively the absorption probabilities and particle lifetimes due to encounters with four of the inner moons of Jupiter (Amalthea, Thebe, Io, and Europa) inside $L < 10$. Our results demonstrate that the resultant average lifetimes of energetic protons and electrons vary dramatically between ~0.1 days and well above 1,000 days, showing a strong dependence on the particle equatorial pitch angle, kinetic energy and moon orbit. The average lifetimes of energetic protons and electrons against moon absorption are shortest for Io (i.e., ~0.1–10 days) and longest for Thebe (i.e., up to thousands of days), with the lifetimes in between for Europa and Amalthea. Due to the diploe tilt angle absorption effect, the average lifetimes of energetic protons and electrons vary markedly below and above $\alpha_{eq} = 67°$. Overall, the average electron lifetimes exhibit weak pitch angle dependence, but the average proton lifetimes are strongly dependent on equatorial pitch angle. The average lifetimes of energetic protons decrease monotonically and substantially with the kinetic energy, but the average lifetimes of energetic electrons are roughly constant at energies <~10 MeV, increase substantially around the Kepler velocities of the moons (~10–50 MeV), and decrease quickly at even higher energies. Compared with the averaged electron lifetimes, the average proton lifetimes are longer at energies below a few MeV and shorter at energies above tens of MeV.

Plain Language Summary As a gaseous and giant planet, Jupiter has the largest magnetosphere in the solar system formed by the interaction between its internal magnetic field and the solar wind flows. Jovian radiation belts are regions of enhanced populations of energetic electrons and protons within its magnetosphere, with an intense and extreme radiation environment. An important feature is that various moons orbit around Jupiter within its magnetosphere, which creates chances for energetic particles to encounter moons, resulting in particle losses and modifying the spatial distributions of energetic particles and their energy spectra and pitch angle profiles. We improve an analytic model to evaluate particle lifetimes around the moon's orbits under the assumption that the moons are ideal insulators, though Europa has tenuous atmosphere and Io has ionosphere. We analyze particle absorption effects by encounters with some of the inner Jovian moons (Amalthea, Thebe, Io, and Europa) and give comprehensive analysis on energy and pitch angle dependences of energetic protons and electrons in Jovian radiation belts. Our improved quantifications of radiation belt particle loss due to moon absorption are suitable to be incorporated with other important physical processes to pursue understanding of the complex variability of the Jupiter's radiation belts.

1. Introduction

The major energy source of the Jovian system is derived from its fast rotation, and its major particle source is from volcanic activities from Io (Bolton et al., 2015). In addition to being plasma sources, large moons embedded within the Jovian magnetosphere can act as candidates responsible for losses of magnetospheric energetic particles as well (Paonessa & Cheng, 1985). The net effect of how moons affect radiation intensities in their environment is determined by the balance of loss processes (such as the moon absorption time scale) and sources (such as how fast new particles are provided by radial transport or local acceleration). Therefore, the moon absorption of radially diffusing energetic particles is recognized as an important physical process that needs to be considered when evaluating the particle dynamics in the Jovian magnetosphere (e.g., Mead & Hess, 1973;

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Nénon et al., 2017, 2018; Santos-Costa & Bourdarie, 2001). In addition to moon absorption, there are many other loss mechanisms, such as charge exchange, energy loss, and pitch angle scattering due to plasma waves (Roussos & Kollmann, 2021). Charge exchange is an important loss process for singly charged ions and only changes the charge state of multiply charged ions (Fujiwara, 1976). At Jupiter, charged particles can loss their energy in many ways, for example, energy loss due to ionization while passing through neutral gas (Kollmann et al., 2013), ring grains (Kollmann et al., 2015), plasma due to collisions with free electrons (Nénon et al., 2018), or being deflected in strong magnetic fields due to synchrotron emission (Santos-Costa & Bourdarie, 2001). Pitch angle scattering by plasma waves can also result in the loss of radiation belt particles by precipitating them into the loss cone (e.g., Nénon et al., 2018; Shprits et al., 2012). However, it is difficult to quantify the relative importance of each loss mechanism, since source and loss processes are highly uncertain. Radial diffusion coefficients at Jupiter scatter by orders of magnitude (e.g., Lejosne & Kollmann, 2020). The calculation of the efficiency of local acceleration depends critically on the wave parameters (e.g., Shprits et al., 2009) that at Jupiter only can be assumed to date. Local acceleration also appears to depend on the location relative to the respective moons (Shprits et al., 2018) in a way that is not fully understood yet. It is evident that the whole complexity of the sources and losses cannot be solved at once. Here we are breaking down the problem and focus only on the particle losses through moon absorption.

The absorptions of energetic particles by moons depend on the particle species, kinetic energy, pitch angle, moon's geometric parameters, and the tilt angle between planetary rotation axis and its magnetic dipole axis (e.g., Hood, 1983; Nénon et al., 2017, 2018; Paonessa & Cheng, 1985; Roussos & Kollmann, 2021; Santos-Costa & Bourdarie, 2001). By analyzing the sweeping processes by the moons, Hood (1983) simulated the particle phase space densities in Saturn's radiation belt and deduced the average particle lifetimes against the satellite absorption loss in a dipole magnetic field. The study of Hood (1983) indicated that particles are likely to escape the absorption when their gyro-radii are comparable to or larger than a given moon diameter or move either latitudinally or longitudinally with a distance comparable to the moon diameter in a gyro-period. By computing the absorption probabilities by the Jovian satellites, Santos-Costa and Bourdarie (2001) proposed a numerical model to estimate the loss rates of electrons induced by the moons, by assuming that the particle gyro-radius is smaller than the moon's size. However, this assumption will break down for protons. Therefore, Kollmann (2012) and Nénon et al. (2018) consider the effect of gyro motion in the physical model of proton radiation belts of Jupiter, following the Paonessa and Cheng (1985). The study of Paonessa and Cheng (1985) have indicated that if the small probability of satellite absorption becomes invalid, the formula used to evaluate the resultant lifetimes of Jovian magnetospheric particles (e.g., Hood, 1983; Nénon et al., 2017, 2018; Santos-Costa & Bourdarie, 2001) needs to be reconsidered. As a result, further investigation is required so as to improve evaluations of average lifetimes of particles against the Jovian moon absorption.

The present study is therefore dedicated to taking into account multiple effects of absorption and deriving an improved satellite absorption model. The improved analytic expressions for the average lifetimes of particles and the absorption probabilities by Jupiter's moons are presented. By numerically quantifying the absorption probabilities and particle lifetimes due to encounters with the inner four Jupiter's moons (Amalthea, Thebe, Io, and Europa) inside $L < 10$, we find that the satellite absorptions of energetic protons are stronger than electrons, showing both energy and pitch angle dependence, and that the particle absorption by Io is more intense than for Amalthea, Thebe, and Europa.

2. Model Description

In this work, we will approximate net losses that can be measured in significant distance from the respective moons. We make assumptions that the moons do not significantly modify Jupiter's magnetic field. This description works best for moons without significant ionospheres (e.g., Neubauer, 1998), as it is the case for Thebe and Amalthea. Europa shows weathering patters resulting from the impact of charged particles on its surface that can be reproduced even without accounting for the detailed field around Europa (Wesley Patterson et al., 2012). If Europa would modify the magnetic field in a way that is significant to energetic particles, the weathering pattern that the particles leave on the surface would be different. Therefore, our approach is still a valid approximation for Europa.

This approximation may be poor for Io (e.g., Bagenal & Dols, 2020). The electromagnetic field depletion in the wake region of Io was observed by Galileo spacecraft, which may change the drift trajectories of electrons and lead to “forbidden zone” that may contribute to the pitch angle “butterfly” distribution (Thorne et al., 1999). By assuming a perfectly conducting Io's ionosphere, Schulz and Eviatar (1977) found that the Jovian's magnetic field will be distorted and particle absorbing characteristics are dependent on both the species and the energy of the incident particle. For very low-energy particles (cold plasma), their adiabatic trajectories will avoid the satellite and escape absorption, while the trajectories of very high-energy particles are undistorted and absorption proceeds as if Io were an insulator. It is also reported by Goldstein and Ip (1983) that the forbidden zone concept fails to explain the depletions observed near Io in the ≥0.5 MeV and ≥5 MeV electron fluxes.

At the same time, in the immediate vicinity of moons that perturb Jupiter's magnetic field, adiabatic changes in the particle distribution may occur and vanish again (e.g., Thorne et al., 1999). Even weak perturbations of particle trajectories near moons can cause the disappearance of particles at unexpected locations, which requires detailed particle tracing in order for this to be understood (e.g., Kotova et al., 2015). Doing so can be challenging particularly for energetic electrons with trajectories that can be sensitive to as weak perturbations as the numerical noise in magnetic field models (e.g., Roussos et al., 2012).

However, irrespective of above complications, radial diffusion is filling in and smoothing out the complicated absorption signature with increasing distance from the moon. A diffused signature can again be described through the simpler considerations that we will discuss just below. This is generally true for weak absorption signatures that refill along the orbit and organize with the downstream distance to the moon (so called microsignatures, e.g., Roussos et al., 2005) and strong signatures that are constant along the moon orbit and organize around the moon's L-shell (so called macrosignatures, e.g., Nénon et al., 2018). This behavior is the reason why we will use relatively simple analytical estimates instead of detailed particle tracing. We expect that residual uncertainties with this approach to be smaller than the current uncertainties in the transport and source processes discussed above.

In order to describe the losses resulted from the sweeping processes of the moons in a dipole magnetic field, we use the particle lifetimes (τ) that can be generally calculated in terms of the probability of absorption (P_{a}) per encounter and the average encounter time (τ_{enc}) (Paonessa & Cheng, 1985), that is,

$$\tau = \frac{\tau_{\mathrm{enc}}}{-\ln\left(1 - P_{\mathrm{a}}\right)}. \tag{1}$$

When the absorption probability P_{a} is sufficiently small (e.g., $P_a \to 0$), Equation 1 can be converted to

$$\tau = \frac{\tau_{\mathrm{enc}}}{P_a}, \tag{2}$$

which has been used by several previous studies (e.g., Hood, 1983; Nénon et al., 2017, 2018; Santos-Costa & Bourdarie, 2001) to quantify the average lifetimes of energetic particles due to the moon absorption. Obviously, as the probability of moon absorption increases, Equation 2 becomes less reliable and even invalid so that the generalized expression of τ (i.e., Equation 1) should be adopted to accurately determine the particle lifetimes, as shown in our subsequent analyses.

Following the study of Brice and Ioannidis (1970), the average encounter time in Equation 1 is given by

$$\tau_{\mathrm{enc}} = \frac{2\pi}{\left|\omega_D - \omega_{\mathrm{Kepler}}\right|}, \tag{3}$$

with ω_D as the particle drift angular velocity in the corotating frame, and ω_{Kepler} as the Kepler angular velocity of the moon. Here, $\omega_D = \omega_{\mathrm{grcu}} + \omega_{\mathrm{corot}}$, where ω_{grcu} is the gradient-curvature drift velocity in the assumed magnetic field (e.g., Thomsen & Allen, 1980), and the ω_{corot} is the rigid corotational velocity of Jupiter. According to Connerney et al. (2020), Europa is located near the inner edge of the magnetodisc. It is also suggested by Tomás et al. (2004) that the change from dipole-dominated magnetic field to current-dominated occurs 12–20 R_J. Thus, here we point out that the assumption of a dipole magnetic field is a common approximation and good assumption inside Europa's orbit. Note that in the corotating frame the moons rotate counterclockwise as viewed from Jupiter's north, and trapped electrons and protons drift around the Jupiter clockwise and counterclockwise, respectively (Mogro-Campero & Fillius, 1976).

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In Equation 1, the absorption probability per encounter is given by (Kollmann, 2012; Kollmann et al., 2013)

$$P_a = a_D a_G a_R a_L. \tag{4}$$

For all these factors it is $0 \leq a_i \leq 1$, where a_i accounts for different mechanisms of escape. Here, we provide analytical expressions to describe these probabilities under the assumption that the moons are spherical and insulating. The latter implies that the moons do not perturb Jupiter's magnetic field in a way that significantly changes the particle trajectories.

In the above equation, a_D is a correction factor for "leapfrogging," considering that the fast-drifting particles can escape the satellite absorption when the drift length δ_D with a half bounce period in the equatorial plane is larger than the moon's effective diameter $\Phi_{\text{eff}} = 2r_m$ (where r_m is the sum of the moon radius r_{mo} and the particle gyro-radius r_g). The calculation of the absorption factor a_D follows (Thomsen et al., 1977)

$$a_D = \begin{cases} \dfrac{\pi}{4\delta_D}\Phi_{\text{eff}} & \text{for } \delta_D \geq \Phi_{\text{eff}} \\ \dfrac{1}{2}\left(\sqrt{1-\dfrac{\delta_D^2}{\Phi_{\text{eff}}^2}} + \dfrac{\Phi_{\text{eff}}}{\delta_D}\arcsin\left(\dfrac{\delta_D}{\Phi_{\text{eff}}}\right)\right) & \text{for } \delta_D < \Phi_{\text{eff}} \end{cases}, \tag{5}$$

where the drift length $\delta_D = \tau_B v_{\text{azi}}/2$ with τ_B as the particle bounce period in a dipole field and the bounce-averaged azimuthal velocity $v_{\text{azi}} = \text{LR}_j\omega_\text{D}$.

Charged particles are likely to escape the moon absorption by their gyro-motion, even if the particle gyro-guiding-center crosses the moon's effective diameter. Several previous studies (e.g., Hood, 1983; Nénon et al., 2017; Santos-Costa & Bourdarie, 2001; Thomsen et al., 1977) have ignored this effect, in the current study we take it into account to investigate its contribution to the overall particle losses by the moon absorption following these studies (e.g., Nénon et al., 2018; Paonessa and Cheng, 1985). The corresponding absorption factor a_G can be given as follows (Hood, 1983; Kollmann, 2012),

$$a_G = \begin{cases} \dfrac{\Phi_{\text{mo}}}{\delta_{G,e}} & \text{for } \lambda_m < \lambda_{\text{mo}} \\ \dfrac{\Phi_{\text{mo}}}{\delta_{G,f}} & \text{for } \lambda_m \geq \lambda_{\text{mo}} \end{cases}, \tag{6}$$

where Φ_{mo} is the moon's diameter, the azimuthal drift distance over the gyro period $\delta_{G,e} = v_{\text{azi}}T_g/2$ with T_g as the gyro-period, the particle traveling distance in the latitudinal direction during a gyro-period $\delta_{G,f} = v\cos(\alpha)T_g$ with v as the particle velocity and α as the particle pitch angle, λ_m is the particle mirror latitude, and the latitude extent of the moon $\lambda_{\text{mo}} = \arcsin(r_{\text{mo}}L/R_j)$. For an equatorial particle, it can encircle the moon when $\delta_{G,e}$ is larger than Φ_{mo}. If the particle has a mirror latitude $\lambda_m$is larger than λ_{mo}, it can "corkscrew" around the moon when $\delta_{G,f} = v\cos(\alpha)T_g$ is larger than the moon diameter (Hood, 1983).

Since the moon's orbit is generally eccentric, a moon can sweep a corridor that is even larger than the moon's efficient diameter. If the particles enter this corridor for an encounter, they can be absorbed by the moon with a certain probability (Paonessa & Cheng, 1985), that is, the orbit absorption factor a_R given by

$$a_R = \frac{\Phi_{\text{eff}}}{\Delta r}, \tag{7}$$

where Δr is the moon sweeping corridor calculated as $\Delta r = 2e_m a + \Phi_{\text{eff}}$ in a dipole magnetic field, with e_m as the eccentricity and a as the semimajor axis length of the moon's Kepler orbit. A similar effect will occur if the plasma flows are not purely azimuthal, as can occur for example, in magnetic fields that are not cylindrically symmetric. We neglect this here as these effects are not significant inward of Europa (e.g., Connerney et al., 2020; Krupp et al., 2001).

In addition, since there is a tilt angle ∼11° between the Jovian rotation axis and the magnetic dipole axis, energetic particles with the mirror latitudes below the magnetic latitude of the moon can escape the encounter absorption. Therefore, a_L denotes the factor associated with the tilt angle absorption. Considering the geometry between the moon and the particle bounce trajectory, the analytic expression to compute a_L can be given as follows,

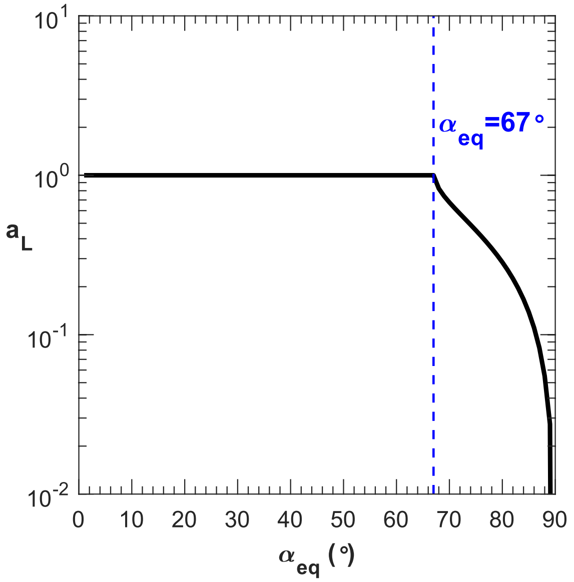

Figure 1. Variation of tilt angle absorption factor a_L with equatorial pitch angle α_{eq}.

$$a_L = \begin{cases} \frac{2}{\pi}\arcsin\left(\frac{\sin\lambda_m}{\sin\theta}\right) & \text{for } \lambda_m \le \theta \\ 1, & \text{for } \lambda_m > \theta \end{cases}, \quad (8)$$

where θ is the tilt angle between the Jovian rotation axis and the magnetic dipole axis.

Overall, Equations 1 and 3–8 form the generalized model to quantify the average lifetimes of energetic particles due to the encounter with Jovian moons. As described above, such an improved model is featured by the applicability for all probability of moon absorption and the consideration of both the particle gyration effect and the tilt angle effect.

3. Numerical Results

Jupiter is well known to have the largest magnetosphere in the solar system and electrons radiation belts with the highest energies (e.g., Mauk & Fox, 2010; Roussos & Kollmann, 2021). Surrounded by intense and energetic radiation belts, the radiation conditions of Jupiter are more extreme inside the Europa's orbit than outside regions (e.g., Kollmann et al., 2017, 2021; Woodfield et al., 2014). Six moons orbit around Jupiter inside $L < 10$ (Metis: $\Phi = 40$ km, $L = 1.84$, and $e_m = 0.0077$; Adrastea, $\Phi = 16$ km, $L = 1.84$, and $e_m = 0.0063$; Amalthea: $\Phi = 167$ km, $L = 2.59$, and $e_m = 0.0075$; Thebe: $\Phi = 98$ km, $L = 3.17$, and $e_m = 0.018$; Io: $\Phi = 3{,}637.4$ km, $L = 6.01$, and $e_m = 0.0041$; Europa: $\Phi = 3{,}121.6$ km, $L = 9.57$, and $e_m = 0.009$). In this study, only Amalthea, Thebe, Io, and Europa are considered, Metis and Adrastea are excluded due to their much smaller diameter than other moons.

3.1. Tilt Angle Absorption Factor a_L

Following Equation 8, the factor $a_L$is determined by the particle pitch angle and the tilt angle between Jupiter's rotation axis and the magnetic dipole axis, regardless of the particle species. At Saturn, this factor is negligible because its magnetic and rotation axes are nearly aligned. Figure 1 presents the results of a_L at Jupiter and indicates that particles with equatorial pitch angles >67° can escape the moon absorptions efficiently, consistent with previous analyses (e.g., Mogro-Campero & Fillius, 1976).

3.2. Absorption of Energetic Protons by Jovian Moons

To investigate the other three moon absorption factors for energetic protons, Figure 2 shows a_D, a_G, and a_R induced by the four Jovian moons as functions of proton equatorial pitch angle and energy. In each panel, the blank margin on the left represents the corresponding loss cone. In Figures 2a–2d, the drift absorption factor a_D increases as the equatorial pitch angle increases. In contrast, a_D first increases and then decreases as the proton energy increases. On one hand, pitch angle increase can increase the moon's effective radius and decrease the proton bounce period, therefore leading to the decrease of proton drift length. On the other hand, the moon's effective radius decreases with decreasing proton energy, and the proton drift length increases as the proton energy increases. Since the decrease of the moon's effective radius or increase of the proton drift length during a half bounce period can result in the decrease of a_D (Equation 5), the pitch angle and energy dependence of a_D is reasonably interpreted to exhibit most effective escape of lower energy protons with smaller pitch angles from the moon absorption along their drift trajectories in considering energy range (100 keV–100 MeV). Additionally, the factor a_D around Amalthea is higher than that of Thebe and of Europa because of the stronger local magnetic field around the Amalthea's orbit. Due to the largest diameter, the value of a_D around Io is also relatively higher. Specifically, for energetic protons with equatorial pitch angles >80° and energies >10 MeV, the drift absorption factor a_D is around 0.7 for Thebe and Europa, but up to ∼1.0 for Amalthea and Io.

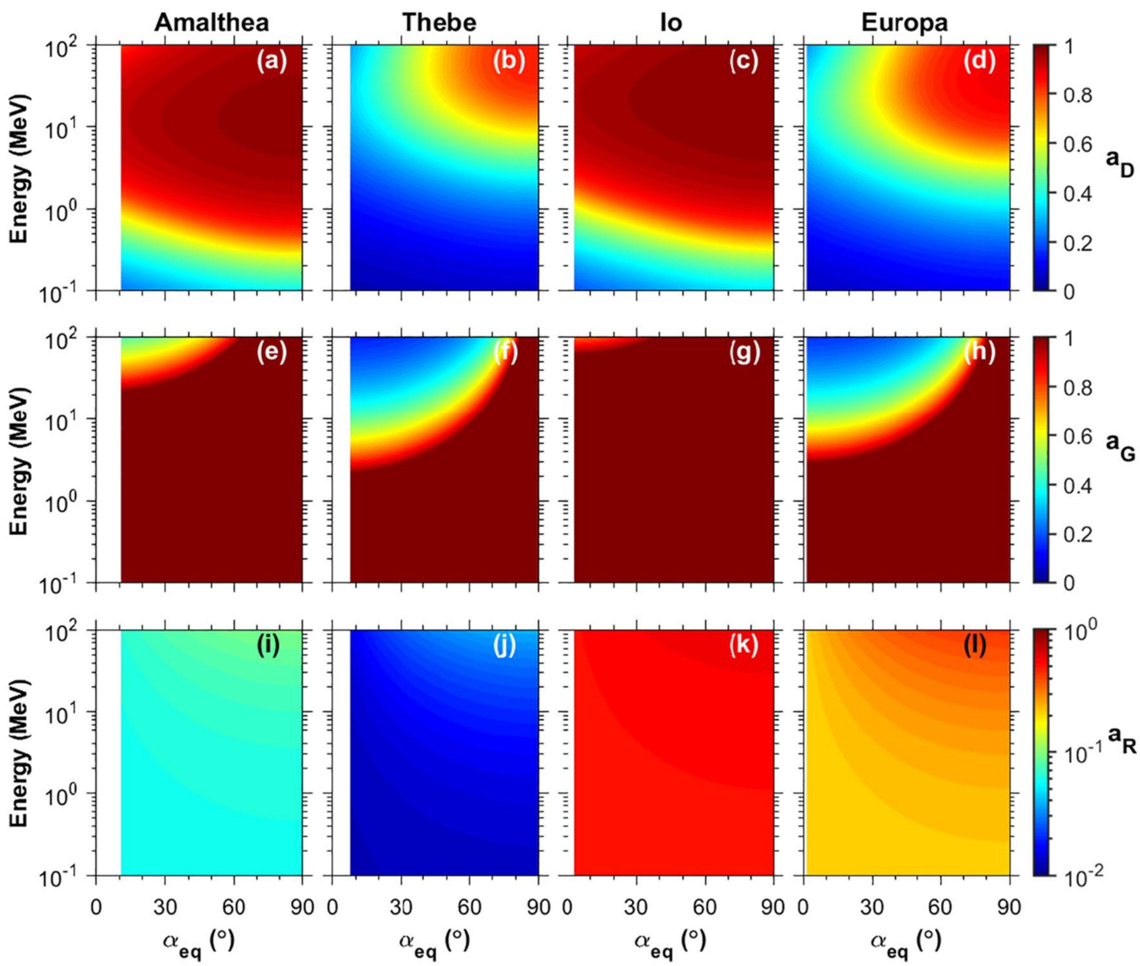

Figure 2. Variations of the drift absorption factor (a_D), the gyro-motion absorption factor (a_G) and the orbit absorption factor (a_R) as functions of proton equatorial pitch angle (α_{eq}) and energy (100 keV–100 MeV) for the indicated four Jovian moons (from left to right: Amalthea, Thebe, Io, and Europa).

Figures 2e–2h display that the gyro-motion absorption factor a_G as function of proton equatorial pitch angle and kinetic energy. Based on Equation 6, for energetic protons with higher equatorial pitch angles or lower energies, their azimuthal drift distances or traveling distances in the latitudinal direction during a gyro-period can decrease accordingly to result in the increase of a_G. Furthermore, protons at very low energies cannot avoid the moon absorption as long as their gyro-radii are much smaller than the moon radius, justifying the result that the factor a_G is around one below certain proton energy for each moon. Due to the most intense local magnetic field around Amalthea orbit and the largest moon radius of Io, the factor a_G is overall larger for Amalthea and Io than Thebe and Europa.

In Figures 2i–2l, the orbit absorption factor a_R, determined by the orbit eccentricity of the moon and the moon's effective diameter, has a trend to increase with both the increasing proton equatorial pitch angle and energy, owing to the increase of the satellite effective diameter. Specifically, Figure 2k shows that the factor a_R is ~0.5 for Io, ~0.2 for Europa, ~0.06 for Amalthea, and ~0.02 for Thebe. Obviously, the orbit absorption probability is largest for Io because of its smallest orbit eccentricity among the four moons.

Based on the results shown in Figure 2, we can compute the overall satellite absorption probabilities (Equation 4), which are shown in Figures 3a–3d together with the average satellite encounter times (Figures 3e–3h) and the average lifetimes of Jovian radiation belt energetic protons (Figures 3i–3l). Mainly due to the effect of a_D, the net probability of satellite absorption manifests an initially increasing and subsequently decreasing tendency with increasing proton equatorial pitch angle and energy. Moreover, due to the effect of a_L, the absorption probability decreases dramatically for energetic protons with equatorial pitch angles >67°. By comparing the absorption

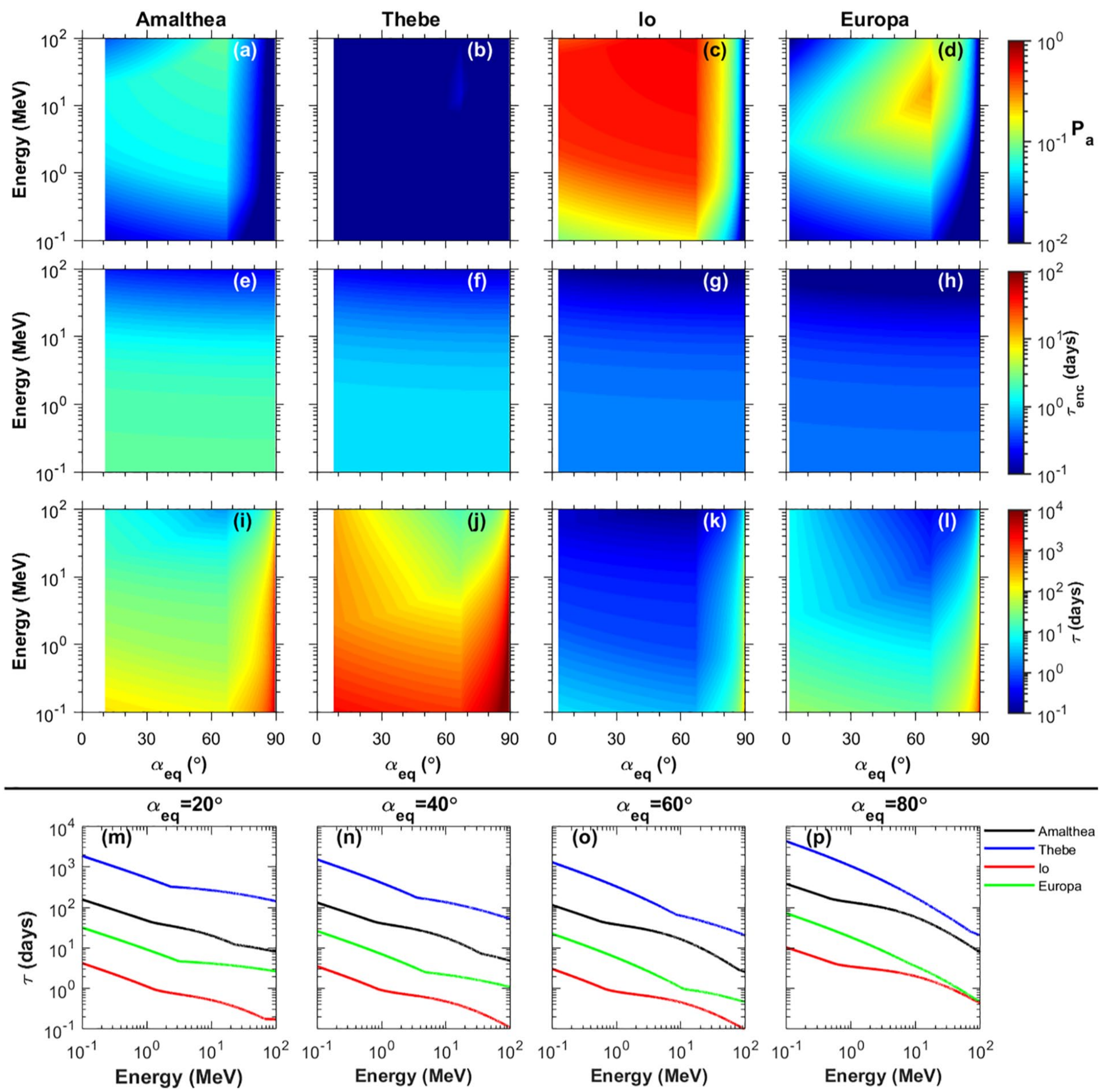

Figure 3. Variations of (a)–(d) the overall satellite absorption probability (P_a), (e)–(h) average satellite encounter time (τ_{enc}), and (i)–(l) average lifetimes of Jovian radiation belt energetic protons (τ) as functions of proton equatorial pitch angle and energy for the indicated four Jovian moons. (m)–(p) Line plots of the average lifetimes of Jovian radiation belt protons with the indicated four equatorial pitch angles (from left to right: 20°, 40°, 60°, and 80°) as a function of particle kinetic energy due to encounters with the color-coded four moons.

probabilities induced by the four Jovian moons, the absorption probabilities by Io are highest with the maximum rate around 0.5 due to its largest a_R than the other moons. In contrast, the absorption probability is smallest for Thebe, with the rate ~0.01.

For the considered four Jovian moons, Figures 3e–3h indicate that the average encounter time between energetic protons and moons varies between 0.1 days and several days, and exhibits a clear trend to decrease with increasing proton equatorial pitch angle and energy, since energetic protons with larger pitch angles and higher energies have larger drift velocities to encounter the moons more quickly. It is noted that the average encounter time between energetic protons and Europa is shortest, as a result of the largest difference between the Kepler velocity and the proton drift velocity.

The resultant average lifetimes of energetic protons, as shown in Figures 3i–3l, manifest strong dependence on the particle energy, equatorial pitch angle and the location of the Jovian satellite. In contrast to that, the proton lifetimes decreases monotonically with increasing kinetic energy, their variations with equatorial pitch angle are somehow complex. For energetic protons with $\alpha_{\mathrm{eq}} > 67°$, their average lifetimes increase obviously and are generally higher than those with lower α_{eq}, mainly due to the variation of the tilt angle absorption effect (Figure 1). For energetic protons with $\alpha_{\mathrm{eq}} \leq 67°$, their average lifetimes decrease with increasing pitch angle, primarily resulting from the combined effect of the drift and gyro-motion absorption. In general, the proton lifetimes due to the satellite absorption are shortest around the Io's orbit (note that Io has the largest moon radius), which can reach the timescales well below 1 day for >~1 MeV protons with $\alpha_{\mathrm{eq}} < \sim 75°$ due to the strong satellite absorption probability and the small satellite encounter time. In contrast, the proton lifetimes due to encounter with Europa are longer by at least an order of magnitude, varying between ~1 and 100 days. In addition, the satellite absorption by Amalthea can cause the loss of Jovian energetic protons on the timescales between several days and ~1,000 days which tend to minimize for >~10 MeV protons with intermediate equatorial pitch angles. Mainly due to the smallest moon radius and the relatively weak magnetic field intensity, Thebe produces the lowest absorption probability among the four satellites, which consequently results in the longest average lifetimes of energetic protons ranging from tens of days to above 1,000 days.

For the illustrative purpose, Figures 3m–3p show the line plots of the average lifetimes of Jovian radiation belt protons with four specific equatorial pitch angles (i.e., 20°, 40°, 60°, and 80°) as a function of particle kinetic energy for the four color-coded Jovian moons. For energetic protons (panels e–h), it is clearly indicated that their average lifetimes decrease monotonically and substantially with the increasing proton energy, varying over four orders of magnitude from 0.1 days to above 1,000 days. The average proton lifetimes show rather small differences between $\alpha_{\mathrm{eq}} = 20°$, 40°, and 60°, with the corresponding loss timescales between ~0.1 and ~4 days for Io, between ~0.6 and ~30 days for Europa, between ~5 and ~100 days for Amalthea, and between ~20 and ~1,000 days for Thebe. Due to the tilt angle absorption effect, the average lifetimes for protons with $\alpha_{\mathrm{eq}} = 80°$ are longer by about an order of magnitude than those with lower pitch angles.

3.3. Absorption of Energetic Electrons by Jovian Moons

In this sub-section, we investigate the losses of radiation belt energetic electrons by encounters with the Jupiter's moons. Similar to Figure 2, Figure 4 illustrates the results of three absorption factors (a_D, a_G, and a_R) induced by the four Jovian moons as functions of electron equatorial pitch angle and energy. For energetic electrons, both the factors a_D and a_G are around 1 for mostly the entire equatorial pitch angles and energy ranges under consideration (panels [a]–[h]), regardless of the moon location. These features are very distinct from those for energetic protons, and can be well explained by the much smaller gyro-radii and drift distances of energetic electrons compared to the protons, which eventually increases the absorption probability of energetic electrons by the Jupiter's moons. In contrast, the factor a_R for energetic electrons (panels [i]–[l]) is much smaller than a_D and a_G, and exhibits the variation profile similar to that of energetic protons (Figures 2i–2l). It is worthwhile to note that the factor a_R is generally lower for electrons than protons, owing to the smaller electron gyro-radii for given particle energy.

Similar to Figures 3a–3l, Figures 5a–5l display the net satellite absorption probabilities, the average satellite encounter times and the average lifetimes of Jovian radiation belt energetic electrons as functions of electron equatorial pitch angle and energy (100 keV–100 MeV) for the indicated four Jovian moons. Overall, the net absorption probabilities of energetic electrons (panels a–c) are roughly similar to those of energetic protons (Figures 3a–3c) for Amalthea, Thebe and Io. In addition, the effect of the tilt angle absorption operates for both particle species to separate the absorption probability patterns below and above 67° equatorial pitch angles. However, there exists quite distinct difference in the electron and proton absorption probabilities for Europa (see Figures 3d and 5d), showing that the rates are constantly ~0.2 for electrons with $\alpha_{\mathrm{eq}} < 67°$. It is also apparent that the electron absorption factors by the Jovian moons manifest weaker pitch angle and energy dependence, compared to the results for energetic protons, mainly due to the dominance of the orbit absorption factor (a_{R}) for electrons.

Figures 5e–5h present the average satellite encounter times for energetic electrons, which are quite different from those for energetic protons. First of all, when the electron azimuthal velocities equal the Kepler velocities of the moons, that is, well above 10 MeV for all the four moons, electrons move with constant distances to the moons and hence avoid the moon absorption efficiently. In addition, the average encounter times of energetic electrons

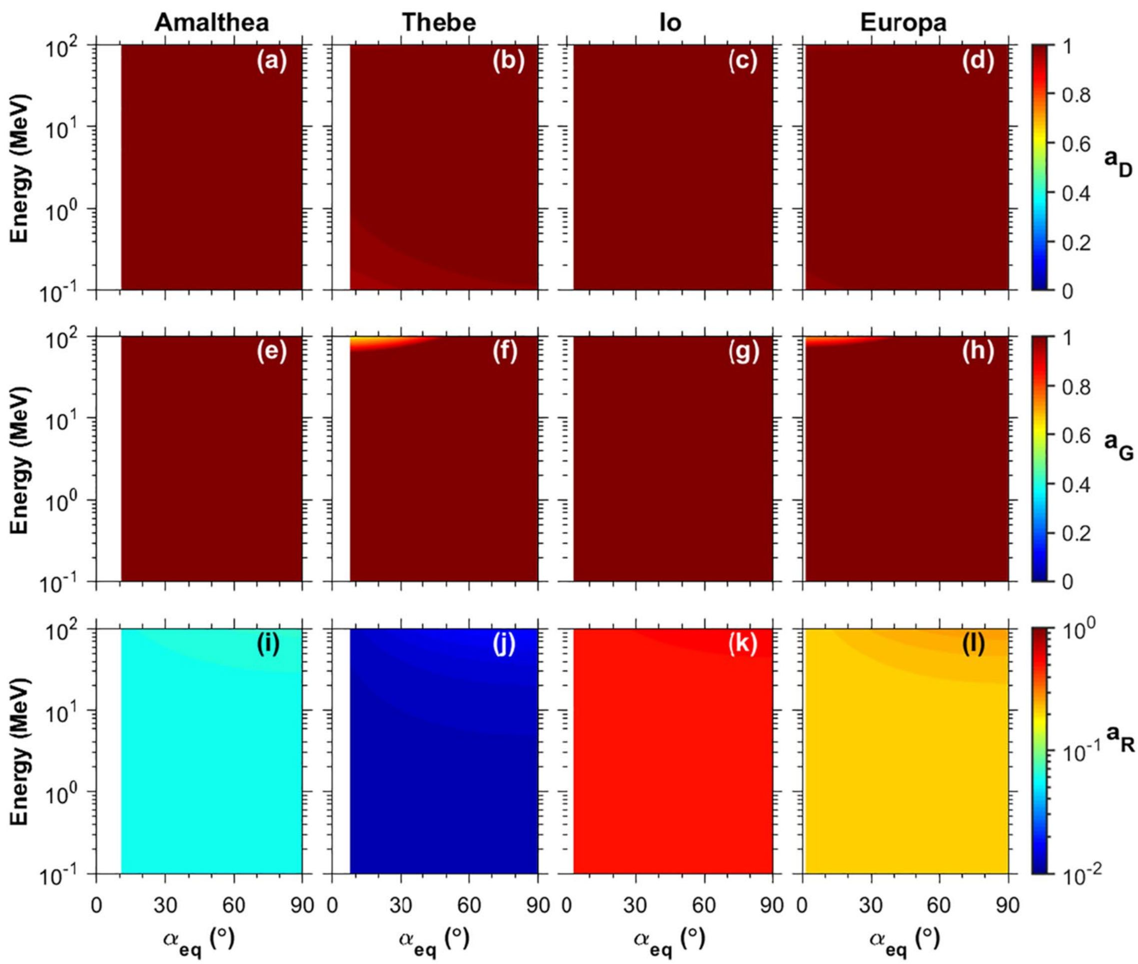

Figure 4. Same as in Figure 2, except for Jovian radiation belt energetic electrons.

with Io and Europa are generally much shorter than those with Thebe and Amalthea, as a result of the smaller Kepler velocities of the former two moons.

The resultant average lifetimes of energetic electrons due to the moon absorption are shown in Figures 5i–5l. For high energy electrons whose azimuthal velocities equal the Kepler velocities of the moons, their lifetimes are extremely long (i.e., >1,000 days). The average lifetimes are also long for electrons with high equatorial pitch angles, which can extend to intermediate pitch angles ~67° for Amalthea and Thebe. For the other populations of energetic electrons, their average lifetimes exhibit weak dependence on the electron pitch angle and energy but rely strongly on the location of the moon. Specifically, the average electron lifetimes are about tens of days for Amalthea, about hundreds of days for Thebe, about 1 day for Io, and about a few days for Europa, respectively.

Figures 5m–5p show the line plots of the average lifetimes of Jovian radiation belt electrons with four specific equatorial pitch angles (i.e., 20°, 40°, 60°, and 80°) as a function of particle kinetic energy for the four color-coded Jovian moons. The average lifetimes of energetic electrons are roughly constant at energies <~10 MeV for all the four equatorial pitch angles and all the four moons, which is consistent with the study of Mogro-Campero and Fillius (1976). When the electron azimuthal velocities approach the Kepler velocities of the moons, the electron lifetimes increase quickly around the corresponding electron kinetic energies between ~10 and 50 MeV. As the electron energy becomes even higher, the corresponding average lifetimes decrease dramatically with the energy to be lost due to the moon absorption. Overall, the average lifetimes of energetic protons and electrons indicate that Io and Europa are important absorption sources responsible for the losses of Jovian radiation belt particles on timescales of tenths of days to several days, while Amalthea and Thebe cause quite inefficient absorption losses of energetic particles mostly on timescales of tens of days and well above.

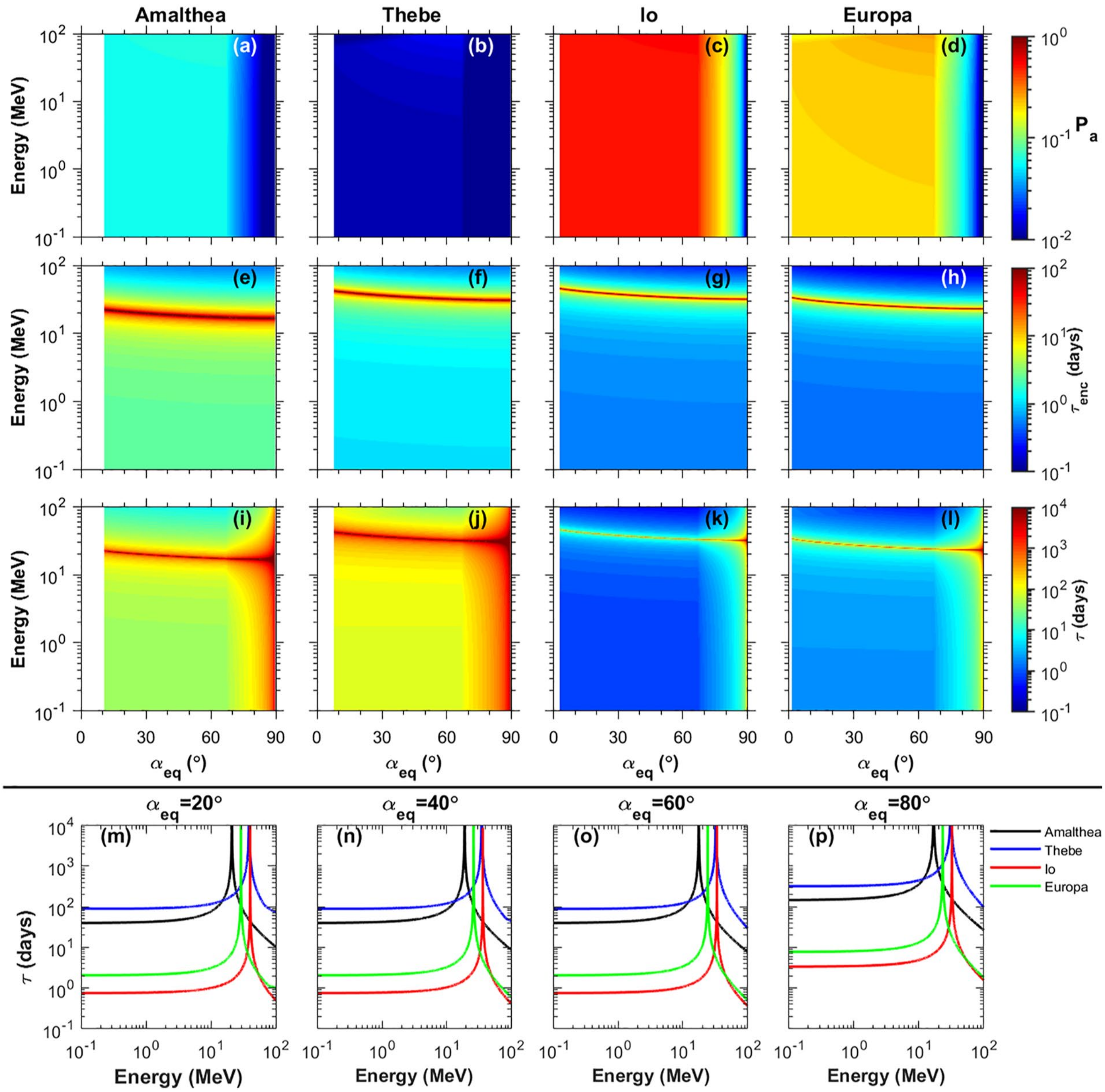

Figure 5. Same as in Figure 3, except for Jovian radiation belt energetic electrons.

4. Conclusions and Discussions

In the present study we have developed an improved model of the moon absorption of Jovian radiation belt particles, which takes into account the combination effect of both the particle motions and moon's geometry and can be applied to all probability of moon absorption. By numerically quantifying the absorption probabilities and particle lifetimes due to encounters with the inner four Jupiter's moons (Amalthea, Thebe, Io, and Europa) inside $L < 10$, we have investigated in details the loss processes of radiation belt energetic particles caused by encounters with the Jovian satellites.

Our major conclusions are summarized as follows:

1. Encounters with the moons of Jupiter act as an important mechanism accounting for the absorption losses of Jovian radiation belt energetic protons and electrons. The resultant average lifetimes of energetic protons and electrons vary dramatically between ~0.1 days and well above 1,000 days, showing strong dependences on the particle equatorial pitch angle and kinetic energy and the moon location.

2. The average lifetimes of energetic protons and electrons due to the moon absorption are shortest for Io (i.e., ~0.1–10 days) as a result of the largest moon radius, and longest for Thebe (i.e., up to thousands of days) as a result of the smallest moon radius and the relatively weak magnetic field intensity, with the lifetimes in between for Europa and Amalthea.
3. Due to the tilt angle absorption effect, the average lifetimes of energetic protons and electrons vary markedly below and above $\alpha_{eq} = 67°$, showing longer lifetimes at $\alpha_{eq} > 67°$. Overall, the average electron lifetimes exhibit weak pitch angle dependence, but the average proton lifetimes are strongly dependent on equatorial pitch angle due to the combined effect of the drift and gyro-motion absorption.
4. The average lifetimes of energetic protons decrease monotonically and substantially with the kinetic energy, but the average lifetimes of energetic electrons are roughly constant at energies <~10 MeV, increasing substantially around Kepler velocities of the moons (~10–50 MeV) and decrease quickly at even higher energies. By comparison, the average proton lifetimes are longer than the electron lifetimes at energies below a few MeV but comparatively shorter at energies above tens of MeV.

We also compare our results of particle lifetimes due to moon absorption with those calculated using the method of Santos-Costa and Bourdarie (2001) (see Figures S1 and S2 in Supporting Information S1). It is clearly shown in Figure S1 in Supporting Information S1 that the method of Santos-Costa and Bourdarie (2001) developed for electrons cannot be readily extended to the cases for protons, since it would underestimate the proton lifetimes for Amalthea, Thebe, and Europa. In addition, that method may overestimate the proton lifetimes for Io at energies >10 MeV and pitch angles <67°, and tend to underestimate the proton lifetimes at energies <10 MeV. Figure S2 in Supporting Information S1 is the same as Figure S1 in Supporting Information S1, but for radiation belt electrons. It is shown that our results of electron lifetime agree well with those calculated using the method of Santos-Costa and Bourdarie (2001) for Amalthea, Thebe, and Europa. For Io, our results of electron lifetime are slightly lower for electrons with energies of <20 MeV at pitch angles of <67°.

It is obvious that encounter absorption by the Jovian moons can play an important role in the dynamic variations of Jupiter's radiation belts (depending on their energy and pitch angle), including the spatial distributions of energetic particles and their energy spectra and pitch angle profiles. According to our numerical results, the absorption losses of Jovian radiation belt energetic particles are very efficient by Io, that is, ~0.1–10 days for protons and ~0.8–3 days for electrons. This is consistent with the relatively low particle fluxes around the Io's orbit (e.g., Santos-Costa & Bourdarie, 2001), however, numerical models suggest that wave-induced scattering into the loss cone may be an even faster process, at least for>MeV energies (Nénon et al., 2017, 2018). Due to the absorption loss by Europa, the particle fluxes can also exhibit a minimum around this orbit. Interestingly, absorption at Europa mostly shows for >10 MeV ions (Kollmann et al., 2021) and otherwise only affects particles in its immediate vicinity (e.g., Paranicas et al., 1998; Kollmann et al., 2018), even though absorption times are smallest for the lowest energies. The reason for this is likely the competition between absorption and other processes that resupply energetic particles at low energies. Europa also may play a role in removing transient Jovian radiation belt particles such as the "C22 transient" (e.g., Hao et al., 2020). While the particle losses caused by encounters with Amalthea and Thebe are much slower, the absorption depletion of energetic particle by these two moons may contribute to the formation of several discrete ion radiation belts found roughly inside $L < 4$ (e.g., Kollmann et al., 2021). Furthermore, on basis of the distinct profiles of average particle lifetimes at different energies with different equatorial pitch angles corresponding to the moon absorption, it is inferred that the pitch angle distribution could likely follow the 90°-peaked type for energetic electrons but exhibit a *V*-type feature for energetic protons and that there may exist a peak of electron fluxes at ~tens of MeV, a feature that currently cannot be resolved with the existing measurements that integrate over large energy ranges. As a consequence, the particle absorption by the Jovian moons needs to be incorporated with other important physical processes, including the wave-particle interactions (e.g., Huang et al., 2018; Kollmann et al., 2018; Nénon et al., 2017, 2018; Shprits et al., 2012, 2018; Summers & Omura, 2007) and radial transport via interchange (Haggerty et al., 2019), diffusion (Lejosne & Kollmann, 2020), and convection (Hao et al., 2020), to pursue improved understanding of the complex variability of the Jupiter's radiation belt, which however is outside the scope of the present study and left for future work.

Data Availability Statement

The numerical results in this manuscript can be obtained from Long (2021).

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References

Bagenal, F., & Dols, V. (2020). The space environment of Io and Europa. *Journal of Geophysical Research: Space Physics*, *125*(5), e2019JA027485. https://doi.org/10.1029/2019JA027485

Bolton, S. J., Bagenal, F., Blanc, M., Cassidy, T., Chané, E., Jackman, C., et al. (2015). Jupiter's magnetosphere: Plasma sources and transport. *Space Science Reviews*, *192*(1–4), 209–236. https://doi.org/10.1007/s11214-015-0184-5

Brice, N. M., & Ioannidis, G. A. (1970). The magnetospheres of Jupiter and Earth. *Icarus*, *13*(2), 173–183. https://doi.org/10.1016/0019-1035(70)90048-5

Connerney, J. E. P., Timmins, S., Herceg, M., & Joergensen, J. L. (2020). A Jovian magnetodisc model for the Juno era. *Journal of Geophysical Research: Space Physics*, *125*(10), e2020JA028138. https://doi.org/10.1029/2020JA028138

Fujiwara, K. (1976). Coulomb-born calculation of charge transfer cross sections of highly-ionized atoms. *Journal of the Physical Society of Japan*, *41*(4), 1350–1355. https://doi.org/10.1143/JPSJ.41.1350

Goldstein, B. E., & Ip, W. H. (1983). Magnetic drifts at Io: Depletion of 10-MeV electrons at Voyager 1 encounter due to a forbidden zone. *Journal of Geophysical Research*, *88*(A8), 6137–6142. https://doi.org/10.1029/JA088iA08p06137

Haggerty, D. K., Mauk, B. H., Paranicas, C. P., Clark, G., Kollmann, P., Rymer, A. M., et al. (2019). Jovian injections observed at high latitude. *Geophysical Research Letters*, *46*(16), 9397–9404. https://doi.org/10.1029/2019GL083442

Hao, Y. X., Sun, Y. X., Roussos, E., Liu, Y., Kollmann, P., & Yuan, C. J. (2020). The Formation of Saturn's and Jupiter's electron radiation belts by magnetospheric electric fields. *The Astrophysical Journal Letters*, *905*(1), L10. https://doi.org/10.3847/2041-8213/abca3f

Hood, L. (1983). Radial diffusion in Saturn's radiation belts: A modeling analysis assuming satellite and ring E absorption. *Journal of Geophysical Research*, *24*(11), 1343–1346. https://doi.org/10.1029/ja088ia02p00808

Huang, J., Gu, X., Ni, B., Luo, Q., Fu, S., Xiang, Z., & Zhang, W. (2018). Importance of electron distribution profiles to chorus wave driven evolution of Jovian radiation belt electrons. *Earth and Planetary Physics*, *2*(5), 371–383. https://doi.org/10.26464/epp2018035

Kollmann, P. (2012). *Sources, sinks, and transport of energetic particles within Saturn's magnetosphere*. Retrieved from https://www.mps.mpg.de/3183759/Dissertation. ISBN 978-3-942171-66-3.

Kollmann, P., Clark, G., Paranicas, C., Mauk, B., Roussos, E., Nénon, Q., et al. (2021). Jupiter's ion radiation belts inward of Europa's orbit. *Journal of Geophysical Research: Space Physics*, *126*(4), e2020JA028925. https://doi.org/10.1029/2020ja028925

Kollmann, P., Paranicas, C., Clark, G., Mauk, B. H., Haggerty, D. K., Rymer, A. M., et al. (2017). A heavy ion and proton radiation belt inside of Jupiter's rings. *Geophysical Research Letters*, *44*(11), 5259–5268. https://doi.org/10.1002/2017gl073730

Kollmann, P., Roussos, E., Kotova, A., Cooper, J. F., Mitchell, D. G., Krupp, N., & Paranicas, C. (2015). MeV proton flux predictions near Saturn's D ring. *Journal of Geophysical Research: Space Physics*, *120*(10), 8586–8602. https://doi.org/10.1002/2015JA021621

Kollmann, P., Roussos, E., Paranicas, C., Krupp, N., & Haggerty, D. K. (2013). Processes forming and sustaining Saturn's proton radiation belts. *Icarus*, *222*(1), 323–341. https://doi.org/10.1016/j.icarus.2012.10.033

Kollmann, P., Roussos, E., Paranicas, C., Woodfield, E. E., Mauk, B. H., Clark, G., et al. (2018). Electron acceleration to MeV energies at Jupiter and Saturn. *Journal of Geophysical Research: Space Physics*, *123*(11), 9110–9129. https://doi.org/10.1029/2018ja025665

Kotova, A., Roussos, E., Krupp, N., & Dandouras, I. (2015). Modeling of the energetic ion observations in the vicinity of Rhea and Dione. *Icarus*, *258*, 402–417. https://doi.org/10.1016/j.icarus.2015.06.031

Krupp, N., Woch, J., Lagg, A., Roelof, E. C., Williams, D. J., Livi, S., & Wilken, B. (2001). Local time asymmetry of energetic ion anisotropies in the Jovian magnetosphere. *Planetary and Space Science*, *49*(3), 283–289. https://doi.org/10.1016/S0032-0633(00)00149-5

Lejosne, S., & Kollmann, P. (2020). Radiation belt radial diffusion at Earth and beyond. *Space Science Reviews*, *216*(1), 19. https://doi.org/10.1007/s11214-020-0642-6

Long, M. (2021). *Losses of radiation belt energetic particles by encounters with four of the inner moons of Jupiter*. figshare. [Dataset]. https://doi.org/10.6084/m9.figshare.16557189.v6

Mauk, B. H., & Fox, N. J. (2010). Electron radiation belts of the solar system. *Journal of Geophysical Research*, *115*(December), 1–19. https://doi.org/10.1029/2010ja015660

Mead, G. D., & Hess, W. N. (1973). Jupiter's radiation belts and the sweeping effect of its satellites. *Journal of Geophysical Research*, *78*(16), 2793–2811. https://doi.org/10.1029/ja078i016p02793

Mogro-Campero, A., & Fillius, W. (1976). The absorption of trapped particles by the inner satellites of Jupiter and the radial diffusion coefficient of particle transport. *Journal of Geophysical Research*, *81*(7), 1289–1295. https://doi.org/10.1029/ja081i007p01289

Nénon, Q., Sicard, A., & Bourdarie, S. (2017). A new physical model of the electron radiation belts of Jupiter inside Europa's orbit. *Journal of Geophysical Research: Space Physics*, *122*(5), 5148–5167. https://doi.org/10.1002/2017JA023893

Nénon, Q., Sicard, A., Kollmann, P., Garrett, H. B., Sauer, S. P. A., & Paranicas, C. (2018). A physical model of the proton radiation belts of Jupiter inside Europa's orbit. *Journal of Geophysical Research: Space Physics*, *123*(5), 3512–3532. https://doi.org/10.1029/2018JA025216

Neubauer, M. (1998). The sub-Alfvnic interaction of the Galilean satellites with the Jovian magnetosphere. *Journal of Geophysical Research*, *103*(E9), 19843–19866. https://doi.org/10.1029/97je03370

Paonessa, M., & Cheng, F. (1985). A theory of satellite sweeping. *Journal of Geophysical Research*, *90*(4), 3428–3434. https://doi.org/10.1029/ja090ia04p03428

Paranicas, C., Cheng, A. F., & Williams, D. J. (1998). Inference of Europa's conductance from the Galileo energetic particles detector. *Journal of Geophysical Research*, *103*(A7), 15001–15007. https://doi.org/10.1029/98JA00961

Roussos, E., & Kollmann, P. (2021). The radiation belts of Jupiter and Saturn. In *Magnetospheres in the solar system* (pp. 499–514). American Geophysical Union (AGU). https://doi.org/10.1002/9781119815624.ch32

Roussos, E., Kollmann, P., Krupp, N., Paranicas, C., Krimigis, S. M., Mitchell, D. G., et al. (2012). Energetic electron observations of Rhea's magnetospheric interaction. *Icarus*, *221*(1), 116–134. https://doi.org/10.1016/j.icarus.2012.07.006

Roussos, E., Krupp, N., Woch, J., Lagg, A., Jones, G. H., Paranicas, C., et al. (2005). Low energy electron microsignatures at the orbit of Tethys: Cassini MIMI/LEMMS observations. *Geophysical Research Letters*, *32*(24), 1–4. https://doi.org/10.1029/2005GL024084

Santos-Costa, D., & Bourdarie, S. A. (2001). Modeling the inner Jovian electron radiation belt including non-equatorial particles. *Planetary and Space Science*, *49*(3–4), 303–312. https://doi.org/10.1016/S0032-0633(00)00151-3

Schulz, M., & Eviatar, A. (1977). Charged-particle absorption by Io. *The Astrophysical Journal*, *211*, L149–L154. https://doi.org/10.1086/182360

Shprits, Y. Y., Menietti, J. D., Drozdov, A. Y., Horne, R. B., Woodfield, E. E., Groene, J. B., et al. (2018). Strong whistler mode waves observed in the vicinity of Jupiter's moons. *Nature Communications*, *9*(1), 7–12. https://doi.org/10.1038/s41467-018-05431-x

Shprits, Y. Y., Menietti, J. D., Gu, X., Kim, K. C., & Horne, R. B. (2012). Gyroresonant interactions between the radiation belt electrons and whistler mode chorus waves in the radiation environments of Earth, Jupiter, and Saturn: A comparative study. *Journal of Geophysical Research*, *117*(11), 1–12. https://doi.org/10.1029/2012JA018031

Shprits, Y. Y., Subbotin, D., & Ni, B. (2009). Evolution of electron fluxes in the outer radiation belt computed with the VERB code. *Journal of Geophysical Research*, *114*, A11209. https://doi.org/10.1029/2008JA013784

Summers, D., & Omura, Y. (2007). Ultra-relativistic acceleration of electrons in planetary magnetospheres. *Geophysical Research Letters*, *34*(24), 1–6. https://doi.org/10.1029/2007GL032226

Thomsen, M. F., & Allen, J. A. V. (1980). Motion of trapped electrons and protons in Saturn's inner magnetospher. *Journal of Geophysical Research*, *85*(A11), 5831–5834. https://doi.org/10.1029/ja085ia11p05831

Thomsen, M. F., Goertz, C. K., & van Allen, J. A. (1977). On determining magnetospheric diffusion coefficients from the observed effects of Jupiter's satellite Io. *Journal of Geophysical Research*, *82*(35), 5541. https://doi.org/10.1029/JA082i035p05541

Thorne, R. M., Williams, D. J., Zhang, L. D., & Stone, S. (1999). Energetic electron butterfly distributions near Io. *Journal of Geophysical Research*, *104*(A7), 14755–14766. https://doi.org/10.1029/1999ja900132

Tomás, A., Woch, J., Krupp, N., Lagg, A., Glassmeier, K. H., Dougherty, M. K., & Hanlon, P. G. (2004). Changes of the energetic particles characteristics in the inner part of the Jovian magnetosphere: A topological study. *Planetary and Space Science*, *52*(5–6), 491–498. https://doi.org/10.1016/j.pss.2003.06.011

Wesley Patterson, G., Paranicas, C., & Prockter, L. M. (2012). Characterizing electron bombardment of Europa's surface by location and depth. *Icarus*, *220*(1), 286–290. https://doi.org/10.1016/j.icarus.2012.04.024

Woodfield, E. E., Horne, R. B., Glauert, S. A., Menietti, J. D., & Shprits, Y. Y. (2014). The origin of Jupiter's outer radiation belt. *Journal of Geophysical Research: Space Physics*, *119*(5), 3490–3502. https://doi.org/10.1002/2014JA019891