The 3D Direct Simulation Monte Carlo Study of Europa’s Gas Plume

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Abstract: Europa has been spotted as having water outgassing activities by space- and ground-based telescopes as well as reanalysis of the Galileo data. We adopt a 3D Direct Simulation Monte Carlo (DSMC) model to investigate the observed plume characteristics of Europa assuming that supersonic expansion originated from the subsurface vent. With a parametric study of the total gas production rate and initial gas bulk velocity, the gas number density, temperature and velocity information of the outgassing plumes from various case studies were derived. Our results show that the plume gases experience acceleration through mutual collisions and adiabatic cooling when exiting from the surface. The central part of the plume with relatively large gas production rates ($10^{29}$ and $10^{30}$ $\text{H}_2\text{O s}^{-1}$) was found to sustain thermal equilibrium and near continuum condition. Column density maps integrated along two different viewing angles are presented to demonstrate the importance of the projection effect on remote sensing diagnostics. Finally, the density profiles at different altitudes are provided to prepare for observations of Europa’s plumes including upcoming spacecraft missions such as JUICE and Europa Clipper.

Keywords: icy moon; Europa; plume

1. Introduction

Europa is an icy moon of Jupiter, and it likely hosts a subsurface ocean, as derived from the diversity of the surface geological features and the magnetic field measurements made by the Voyager and Galileo missions (e.g., [1–4]). Recently, outgassing plumes have been inferred to occur on Europa. These observations include (1) the local density inhomogeneity of the atomic O and H aurora emissions observed by the Hubble Space Telescope (HST), the emission intensities of which are consistent with electron-impact dissociation of water molecules [5]; (2) the HST observation of absorption features shown in the UV continuum of Jupiter during Europa’s transits [6–8]; (3) the water molecules observed in the infrared wavelength by the Keck Observatory [9]. In addition, reanalysis of the Galileo data, including the magnetic field and plasma measurements, also inferred that Europa had eruptions [10–12].

All of the above reports suggested that the plumes originated from various latitudinal regions in the southern hemisphere, except for no latitudinal information of the Keck result due to the fact of its observational configuration. Neither the exact source location nor the venting mechanism (i.e., plume dynamics) are explicitly disclosed. The gas thermal velocities were required to be at least 0.5 and 0.7 km s$^{-1}$ to arrive at the altitude of the observed peaks of ~100 km [8] and ~200 km [5], respectively, assuming that the plume
material follows a ballistic motion. The transverse water column densities of $\sim 10^{20} \text{ m}^{-2}$ and $1.8 \times 10^{21} \text{ m}^{-2}$ were derived by [5,8], respectively, while the disk-averaged column density derived from Keck measurements by [9] suggested $1.4 \times 10^{19} \text{ H}_2\text{O m}^{-2}$. Although the possible projection effect on plume morphology is discussed later, it could suggest that a mixture of various outgassing activities occurred in random places on Europa. The durations of Europa’s plume eruptions are not known either, which are only provided with the integrated observation time of several hours (e.g., $\sim 2.5$ h [9]; $\sim 1$ h [8]; $\sim 7$ h [5]). The signatures of Europa’s plumes inferred by the Galileo data (i.e., the E12 flyby at the closest-approach altitude of $\sim 200$ km [12] and the E26 flyby at the closest-approach altitude of $\sim 350$ km [10]) were roughly consistent with the small-scale plume characteristics suggested by [5]. The in situ measurements of Galileo could give better constraints on the source regions, which were both in the Southern Hemisphere and trailing side. However, existing observations also indicated that the Europa’s outgassing activity may not be similar to Enceladus’ persistent plumes but were sporadic and/or intermittent events [9,13,14].

In addition to recent observations, modeling efforts have been made to investigate Europa’s plume morphology and its consequences. For example, some surface features on Europa could be associated with its plume emplacements via cryovolcanism [15,16]. Using a ballistic trajectory model, [16] found that the small-scale plumes with a low eruption velocity ($<0.3 \text{ km s}^{-1}$) could account for the dark material deposited around the ridges, lenticulae and lineae shown in the Galileo images. Ref [17] examined the morphological and spectral signatures of the possible plume deposits and used the latest HST observations to constrain the eruption velocity to be $0.03$–$1.0 \text{ km s}^{-1}$. Ref [18] modeled Europa’s dust plume morphology and studied its surface deposition effect assuming that the driving mechanism is similar to that of Enceladus [19]. When investigating Europa’s global exosphere mainly generated from sputtering and thermal adsorption, [20] also added an assumed plume source with a production rate of $10^{28} \text{ H}_2\text{O s}^{-1}$ in the south polar region. Their modeling results showed that a significant gas density enhancement could exist near the plume source region (i.e., lifetime on the order of magnitude of $10^5$ s). Ref [21] used a Monte-Carlo model with a ballistic approach to simulate the plume profiles from three different source mechanisms and found out that the source cannot be determined by comparing the simulated atomic H and O emissions with the existing HST observations [5,22].

In this work, a DSMC model was developed to investigate the plume characteristics of Europa. The direct simulation Monte Carlo (DSMC) method proposed by [23] is suitable for studying the rarefied gas flow by solving the Boltzmann equation. For example, the physical processes and structures of the planetary jets and plumes can be adequately described by the DSMC model with a broad flow regime ranging from close to semi-continuum near surface to a collisionless condition at high altitudes (e.g., [24–30]). Recently, [31] used a DSMC model to examine Europa plumes with a primary variable of the Mach number which dominates the plume expansion. Their Mach number is determined by the throat-to-vent area ratio assuming that the supersonic expansion originated from a subsurface vent similar to Enceladus’ condition [19]. Understanding the plume dynamics above surface, therefore, can be used to probe its subsurface vent properties. In addition, a canopy shock layer can be formed in the top of plume with a high flow mass rate of $\sim 1000 \text{ kg s}^{-1}$, which would limit the overall plume height [31].

We conducted a systematic study on the effects of the total gas production rate and initial gas bulk velocity with an assumption of supersonic eruption from subsurface. The details of our DSMC model and justifications of the model inputs are presented in Sections 2 and 3, and they show the simulated plume results for the Knudsen number, gas temperature, number density and velocity distributions. The projection effect on the plume morphology integrated along two different viewing angles is also discussed. The density vs. horizontal distance profiles of the simulated plumes at different altitudes are provided for comparisons with any possible future observation. Comparisons with existing plume observations and the important consequences of Europa’s outgassing activity are discussed at the end of Section 4. Finally, a summary of our work is given in Section 5. The modeling
results of both assumed that the gas production rate and gas bulk velocity (such as plume height, gas temperature, velocity and density distribution) can be used to improve scientific interpretations of space- and ground-based telescope observations of Europa’s plumes. It is also helpful for the designs of the in situ measurements of future spacecraft missions, such as the JUpiter Icy moons Explorer (JUICE; [32]), which will explore Jupiter and its three large icy moons in depth, and the Europa Clipper [33], to characterize further information about the plume source region on Europa.

2. Materials and Methods

2.1. General Description

The DSMC method is a particle-based method to simulate gas flow with a large number of particles. This method was proposed by [23], and it solves the Boltzmann equation for all regions of rarefaction. The Knudsen number (Kn) indicates the rarefaction of gas flow and is defined as Kn = \( \frac{\lambda}{L} \), where L is the characteristic length and \( \lambda \) is the local mean free path.

In this work, Europa’s radius (1560 km) was used as a characteristic length, L, to investigate the global structure of Europa’s plumes. If Kn > 0.001, the continuum assumption with a conventional no-slip boundary condition breaks down [34]. The PDSC++ code used in the present study is a 3D parallelized DSMC code including several features: unstructured mesh, variable time-step scheme, domain re-decomposition and automatic steady-state detection scheme [35–39]. It has also been successfully applied to the modeling of cometary outgassing [40–45].

To calculate the plume of Europa, we built an unstructured grid with 3,987,633 tetrahedron cells. The cell size was set to be smaller than the local mean free path of the molecules. The size of the simulation box was approximately 12 Europa’s radii. The initial gas temperature was assumed to be in thermodynamic equilibrium (i.e., kinetic temperature equal to rotational temperature) when exiting from the surface boundary condition. The low temperature (<120 K) [36] on the surface of Europa suggests that the water molecules will mostly re-condense when they collide with the boundary of Europa’s surface. Therefore, the simulation particles in the model will be removed when they collide with the surface. A general DSMC calculation can be described as following:

1. Set initial state and read system data: Before calculation, the DSMC program must set-up a grid for the calculation and then input the initial condition and boundary condition;

2. Move all particles: In the calculation of each time step, the simulation gas particles travel a distance with their velocities. The particles that leave the simulation domain are removed;

3. Introduce new particles: After moving all of the particles, new particles are added into the simulation domain from the boundary of the source region;

4. Sort particles and calculate collisions: In this phase, all particles are indexed in the simulation domain and the collision pairs identified, which depends on the local number density, and the new velocities after collision are calculated. In this work, we used the variable soft sphere (VSS) model for the collision. In addition, collisions also allow for energy transfers between the translational and internal (i.e., rotational) mode;

5. Sample the flow and check the steady-state flow: In each cell, the macroscopic properties of flow are sampled from the microscopic properties of each particle. When the flow reaches the steady state, by checking the convergence of the total particle number, velocity and temperature, the flow field will be stored. The final result of the gas flow will be calculated by taking the average of the sufficient sampling.

2.2. A Parametric Study of the Gas Production Rate and Gas Bulk Velocity

In this work, we examined the physical processes and structures of supersonic gas plumes of Europa. Neither grain formation due to the fact of condensation nor collision with grains were taken into account. The effects of grains on the planetary plume morphology were found to be negligible (e.g., [44]). The only loss process of the water molecule
considered here was to re-impact the surface, meaning that the modeled plume reached a steady state not much longer than the particle flight time (i.e., on the order of several thousand seconds). By the same token, the water loss to photolytic, electron-impact and ion-neutral reactions affected by Jupiter’s magnetospheric plasma was not included because of the much longer reaction timescales (i.e., \( \sim 10^5 \) s [45]) compared to the particle flight time. Coriolis force and centrifugal force were found to be negligible when the particle flight time was much shorter than Europa’s rotation period. A circular source area was assumed with a radius of 20 km near a pole on Europa. Note that this is not a representative size of a realistic vent on Europa, because there is no actual measurement and/or solid evidence of the subsurface vent size on Europa. Regardless of the meter-sized vent on Enceladus, suggested by [19], the vent size on Europa can be expected to be broader due to the fact of its larger mass (e.g., [46]). A large modeled vent size can be seen as a collective effect of many small vents located in a limited region, and we focused only on the macroscopic phenomenon assuming that these smaller plumes do not have strong interactions to significantly modify the overall plume morphology. A similar approach has also been used by [30] to study Io’s volcanic plumes with a “virtual” vent radius of 16 km in a DSMC model. In addition, the observable outgassing properties, such as plume height and width, were found to change only in a range of 10–20% when modifying the modeled parameters such as the vent size. In addition, the spatial resolution (~200 km) and sensitivity in the HST images (e.g., [5]) are insufficient to distinguish the collisional part and non-collisional part of observed plumes. Our approach is thus adequate for use in observing plume morphology (i.e., plume height and width) to investigate the gas eruption properties near the surface. Although it is a compromising strategy between the computational time and spatial resolution, the modeling results is a useful first step for comparing with remote sensing observations.

As discussed above, existing observations do not give a clear and consistent picture of Europa’s plume eruption. In addition, it has also been observed that Enceladus’ outgassing activities could be a mixture of various gas emission rates from different source locations, narrow and high-altitude jets as well as diffusive and low-altitude plumes (e.g., [47,48]). Therefore, we studied Europa’s plume activity with a large parametric space mainly relying on what we learned from Enceladus. In the simulations, the initial gas thermal temperature of Europa’s plume was assumed to be 180 K based on the source temperature of Enceladus’ plume gas [49], considering the lack of direct constraints of Europa’s plumes. The previously published temperatures of Europa’s gas plumes were indirectly derived from the altitudes of the observed signals, assuming plume material following ballistic trajectories with their gas thermal velocities being able to reach (e.g., \( >230 \) K [5]). Note that the plume peak altitudes derived from observations may not represent the actual plume top due to the projection effect (i.e., the line-of-sight effect and the unknown source region) as is discussed in Section 3.3. The supersonic and high-altitude jets (i.e., high Mach number) and the diffusive and low-altitude plumes (i.e., low Mach number) observed in Enceladus, on the other hand, suggested both medium- and high-velocity ejections (e.g., [47,48,50–52]). Along this line, a systematic study of the gas bulk velocities, from subsonic (0.35 km s\(^{-1}\)) to supersonic conditions at 0.5 km s\(^{-1}\), 0.75 km s\(^{-1}\) and 1.0 km s\(^{-1}\) with averaged Mach numbers between 1 and 2, was carried out in this work.

Finally, three water gas production rates of \( 10^{28} \) s\(^{-1}\), \( 10^{29} \) s\(^{-1}\), \( 10^{30} \) s\(^{-1}\) were considered in the simulations. These values appear to be much higher than the Enceladus plume source rates (i.e., in the order of \( 10^{28} \) s\(^{-1}\)), with the middle case being comparable to the values derived by [5] \((-2.3 \times 10^{29} \) H\(_2\)O s\(^{-1}\)) and [9] \((-8 \times 10^{28} \) H\(_2\)O s\(^{-1}\)). It was also found that the Europa plume mass was ~100 times that of Enceladus when [53] compared the Enceladus plume material measured by Cassini UVIS (Ultraviolet Imaging Spectrograph Subsystem) with the absorption features of Europa’s plumes seen in the HST images [2]. The initial model inputs for the six case studies are summarized in Table 1. While cases 1–3 were simulated with the same gas bulk velocity of 0.5 km s\(^{-1}\) to study the effect of varying gas production rate on the plume morphology, the influence of initial gas bulk velocity was
examined in cases 4–6 with the same Q = 10^{29} H_2O s^{-1}. A special case 7 was included to investigate the possible stealth plume activity under the current detection limits (i.e., a very low gas production rate of 10^{26} H_2O s^{-1}) which could be discovered by the upcoming space missions (discussed in Section 4).

Table 1. The initial conditions in the case studies with a circular source area of a radius of 20 km. * A special case 7 simulated a possible stealth plume with a circular source area with a diameter of 10 km.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
<th>Case 7 *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Production Rate (H_2O s^{-1})</td>
<td>1 × 10^{30}</td>
<td>1 × 10^{29}</td>
<td>1 × 10^{28}</td>
<td>1 × 10^{29}</td>
<td>1 × 10^{29}</td>
<td>1 × 10^{29}</td>
</tr>
<tr>
<td>Gas Bulk Velocity (km s^{-1})</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.35</td>
<td>0.75</td>
<td>1.0</td>
</tr>
<tr>
<td>Gas Temperature (K)</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Mach Number</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>0.8</td>
<td>1.6</td>
<td>2.2</td>
</tr>
<tr>
<td>Simulated Plume Height (km)</td>
<td>~350</td>
<td>~350</td>
<td>~350</td>
<td>~250</td>
<td>~500</td>
<td>~800</td>
</tr>
<tr>
<td>Simulated Plume Width (km) ***</td>
<td>~80</td>
<td>~80</td>
<td>~80</td>
<td>~90</td>
<td>~50</td>
<td>~50</td>
</tr>
</tbody>
</table>

* A special case 7 simulated a possible stealth plume with a circular source area with a radius of 5 km. ** Hard to define; no obvious canopy layer shown in the plume top due to the very small gas production rate. *** Here, we used the full width half maximum of the 50 km profile shown in the section of Results.

3. Results

Here we show the simulation results of six case studies to investigate the physical structure of Europa’s outgassing plume expanding from surface to high altitude. Both effects of the total gas production rate and gas bulk velocity on the plume morphology and dynamical process are discussed.

3.1. Knudsen Number, Gas Temperature and Thermal Equilibrium

Figure 1 (column a) shows the modeled local Knudsen number, Kn, along the plume symmetric plane. It can be seen that the Kn varied by several orders of magnitudes across the plume. The gas flow in the low-altitude and central region of the plume shows a near continuum condition (Kn ≤ 0.01) where frequent gas collisions occur. Then, it expands to the collisionless condition (Kn ≥ 1) at a high altitude (i.e., transition region). The transition altitude where the flow starts to deviate from continuum was highest (~0.5 Europa radius above surface) with the highest gas bulk velocity of 1.0 km s^{-1} (Figure 1, case 6(a)). In addition to the effect of initial gas bulk velocity, the transition height slightly decreased with the decreasing gas production rate, particularly for 10^{28} s^{-1} due to the fact of insufficient gas collisions (see Figure 1, case 3(a)).

The degree of local thermal equilibrium, represented by γ, is shown in Figure 1 (column b). γ is defined to be “the absolute value of (T_{trans}/T_{rot} − 1)”, where T_{trans} and T_{rot} are the gas translational temperature and rotational temperature, respectively. When γ is close to zero, the gas flow approaches thermal equilibrium (i.e., the translational temperature equal to the rotational temperature), which mostly occurs in the dense part of the plume along its central line and its upper layer. At a very top of the plume, γ becomes larger and T_{trans} deviates from T_{rot}. The energy in each mode (i.e., translational and rotational temperature) may remain “locked” without sufficient gas collisions allowing for energy transfer in different modes. By the same token, the translational and rotational temperatures differ from one another along the lateral edges of the plumes (i.e., red color in the bowtie-shaped region as discussed below) where the gas collision frequency is too low to maintain thermal equilibrium. Similar features are also reflected in the Kn plots. The chaotic regions outside of the major plume tops (i.e., the red colored regions) were
the result of a very few particles scattered by gas collisions. As expected, the degree of thermal equilibrium depends on the collision frequency, which is also controlled by the gas production rate (see cases 1–3 in Figure 1b for comparisons). The distribution of the degree of thermal equilibrium is generally consistent with the one of Kn, where a smaller Kn indicates a condition closer to thermal equilibrium (i.e., smaller $\gamma$). Figure 1 (column c) presents the gas translational temperature distributions. The gas translational temperature along the center line of the plume rapidly dropped from the initial 180 K to below 100 K within an altitude of ~100 km. This was due to plume expansion that causes adiabatic cooling primarily in the low altitude region. The statistical noise above the plume tops (Figure 1 case 6(c)) were the result of low counting statistics in this region, which is also seen in the lateral sides of the plume bottom (i.e., the high temperature region) where too few particles were recorded.

![Figure 1.](Image)

Figure 1. Cont.
Figure 1. Column a (Left): Results of the local Knudsen number, $K_n$ (shown in contours with a color scale). When $K_n > ~0.01$, the gas flow started to deviate from continuum. Column b (Middle): Degree of thermal equilibrium represented by $\gamma$ (shown in contours with a color scale of $\gamma$). $\gamma$ is defined to be “the absolute value of (T_{trans}/T_{rot}) minus 1”. A $\gamma$ closer to 0 indicates that the gas flow is approaching thermal equilibrium. Column c (Right): Gas translational temperature distribution (shown in contours with a color scale in units of K).

3.2. Gas Number Density and Velocity Distributions

The number density distributions of the simulated plumes are shown in Figure 2 (column a). Because of expansion, the gas number density dropped rapidly with the increasing altitude. With the same initial velocity, the gas number density generally increased with the larger gas production rate (cases 1–3(a) in Figure 2). There were also some distinct features such as the bow-shape structure (i.e., canopy) at the plume top and the “bowtie” pattern in the lateral sides of the plume in the low-altitude region. Both features are seen in Figure 1 as well. The enhanced density shown in the “bow” shape at the plume top was due to the sum of two particle populations (i.e., upward flow and downward flow) that approached zero velocities. This feature was mostly obvious in the plumes produced with
a high gas production rates of $10^{30} \text{ s}^{-1}$ and $10^{29} \text{ s}^{-1}$. The importance of the canopy shock layer on plume morphology has also been discussed by [31]. The “bowtie” pattern represents the voids in the lateral sides of the plume where very few particles travel through. With the same gas production rate, the effect of initial gas ejection velocity on the plume morphology is presented in Figure 2 for cases 2 and 4–6 for $Q = 10^{29} \text{ s}^{-1}$, which clearly shows that the reducing gas ejection velocity led to a smaller and much denser plume.

**Figure 2.** Cont.
Figure 2. Column a (Left): Number density distribution (shown in contours with a color scale in units of # m$^{-3}$). The dashed, horizontal lines in case 1 represent four heights above the surface at 50, 100, 200 and 400 km. Column b (Right): Gas velocity distribution (shown in contour with a color scale in units of m s$^{-1}$). Gas flow streamlines are presented too.

The gas velocity distribution of the plume is shown in Figure 2 (column b). Overall, the gas velocity decreased with increasing altitude because of Europa’s large gravity. However, when examining the velocity evolution below the altitude of ~100 km, it was found that
the gas velocity appeared to be slightly larger than the initial gas bulk velocity (i.e., see the obvious depictions in cases 5 and 6; other cases do not clearly show this due to the color scale). This can be attributed to the acceleration due to the fact of gas collision and adiabatic cooling during expansion. The averaged gas flow velocity along the central line of plume can be accelerated to ~0.6, 0.65, 0.85 and 1.05 km s$^{-1}$ from its initial gas bulk velocity of 0.35, 0.5, 0.75 and 1.0 km s$^{-1}$, respectively. Because of this acceleration effect, therefore, the plume top from the DSMC modeling would be much higher than the one with purely ballistic motion (discussed in Section 4). The degrees of lateral expansion resulting from gas collisions of various gas production rates are also shown in cases 1–3 in Figure 2. Following the streamlines, the plume particle speed also increased when returning to the surface. The plume gas molecules mostly fall back to Europa’s surface, since the initial ejection velocity is lower than Europa’s escape velocity of ~2.0 km s$^{-1}$. Figure 3 (Left) shows the plume profiles of number density as a function of distance at four altitudes of 50, 100, 200 and 400 km (i.e., a horizontal cut through the plume). It is clearly shown that the plume width (e.g., the FWHM (full width half maximum) of the 50 km profile) was mainly controlled by the Mach number, while the gas collision (determined by the gas production rate) played a minor role (please also see the summary in Table 1). The distinct density profiles presented in Figure 3 (Left) can be used to compare with future in situ neutral particle detection to examine the plume properties of Europa outgassing activities.

Both axes are arbitrary and presented in units of Europa radius. Poor statistics are shown above the major plume tops (i.e., red color). This is also shown in the lateral sides of the plume bottoms where too few particles were counted.

Both axes are arbitrary and presented in units of Europa radius.

The profiles are given in a mocked spacecraft trajectory flying across the plume horizontally (i.e., parallel to the $x$-axis in Figures 2a and 4a) at different altitudes. The $x$-axis is presented in units of Europa radius.

3.3. Column Density

The simulated plume morphologies with the integrated column densities along two different viewing angles of 90° (i.e., perpendicular to the plume symmetric axis) and 45° are presented in Figure 4. Figure 4 (column a) (along a line of sight of 90°) shows that the height of the dense plume (i.e., red/pink color) was mainly determined by the initial gas ejection speed, and the plume heights were ~250, ~350, ~500 and ~800 km for 0.35, 0.5, 0.75 and 1.0 km s$^{-1}$, respectively (see the summary in Table 1). As discussed above, the plume height appears to be much higher than the one computed with purely ballistic motion as a result of acceleration due to the gas collisions in the low-altitude region. For example, a ballistic particle with an initial ejection speed of 0.75 km s$^{-1}$ could reach a maximum height of only ~210 km, less than half of the modeled height. On the other hand, when viewing from 45°, as shown in Figure 4 (column b), the plume extended down to the surface and covered a part of Europa’s disk. It is evident that the observed plume morphology strongly depended on the viewing geometry. This also shows that it is not an easy task, without any other supplementary information, to trace back a plume seen in one 2D projected image to its exact source region. The column density profiles (integrated along a line of sight of 90°), as a function of horizontal distance to the plume symmetric axis at four altitudes of 50, 100, 200 and 400 km, are shown in Figure 3 (Right) The maximum column densities at an altitude of 50 km simulated with the water production rates of $10^{28}$, $10^{29}$ and $10^{30}$ s$^{-1}$ were in the order of $10^{20}$, $10^{21}$ and $10^{22}$ m$^{-2}$, respectively.

The contour is shown in a color scale in units of # m$^{-2}$. Both axes are arbitrary and presented in units of Europa radius.
Figure 2. Column a (Left): Number density distribution (shown in contours with a color scale in units of $\text{# m}^{-3}$). The dashed, horizontal lines in case 1 represent four heights above the surface at 50, 100, 200 and 400 km. Column b (Right): Gas velocity distribution (shown in contour with a color scale in units of $\text{m s}^{-1}$). Gas flow streamlines are presented too.

Figure 3. Left: The plume profiles of number density (#/m$^3$) as a function of horizontal distance at four altitudes of 50, 100, 200 and 400 km. Right: The plume profiles of column density (integrated along a line of sight of 90 degrees) as a function of horizontal distance at four altitudes of 50, 100, 200 and 400 km.
Figure 4. Cont.
Figure 4. Column a (Left): Column density integrated along a line of sight of 90 degrees from Europa’s pole (i.e., perpendicular to the paper). The dashed, horizontal lines in case 1 represent four heights above the surface at 50, 100, 200 and 400 km. Column b (Right): Column density integrated along a line of sight of 45 degrees from Europa’s pole (i.e., toward the reader).
4. Discussion

Although the observed plume parameters (such as source location, outgassing rate and gas ejection velocity) derived from the existing observations did not give a consistent picture, it could suggest a mixture of various outgassing mechanisms as discussed above. Compared with the HST atomic emission data [5] and the Galileo E12 measurements [12] obtained at an altitude of ~200 km, our simulation cases with a gas production rate of Q = 1.0 × 10^{20} \text{ s}^{-1} (i.e., see cases 2, 4, 5 and 6 in Figure 3b) produced averaged column densities in the order of 10^{20} \text{ m}^{-2}, which is consistent with the derived column densities of the HST and Galileo observations when taking into account the spatial resolution limited by the observations (i.e., ~100 km [5]). In addition, the peak column densities measured by [8] (~1.8 × 10^{21} \text{ m}^{-2}) and by [9] (~1.8 × 10^{19} \text{ m}^{-2}) are closer to the simulated cases with production rates of 10^{20} \text{ s}^{-1} (case 1) and 10^{28} \text{ s}^{-1} (case 3), respectively. The simulated plume tops of the initial gas bulk velocity of 0.35 and 0.5 km \text{ s}^{-1} reached an altitude of ~250 and ~350 km, which are also in agreement with the HST and Galileo measurements [9,10,12]. These initial gas velocities were smaller than the ones derived by the HST observations in which the authors assumed a ballistic particle motion [5,8]. Moreover, the plume morphologies (i.e., the height and width) simulated from the DSMC modeling were much different from the purely ballistic motion due to the gas collisions that occurred in the low-altitude region. Moreover, it was difficult to interpret the observed 2D projection images, because the combined effect of the viewing angle and the gas velocity degenerated, meaning that the solution may not be unique if the plume source region is not known. The in situ measurements of the upcoming ESA JUICE and NASA Europa Clipper missions with finer spatial resolution are expected to reveal the exact source regions and the detailed plume structures such as the gas density, velocity and temperature distributions. These parameters are important tools to probe its subsurface vent properties and investigate its surface deposition effect as discussed below. Finally, the special case 7 (with an initial $V_{\text{bulk}} = 0.35 \text{ km s}^{-1}$ and $Q = 1 \times 10^{26} \text{ H}_2\text{O s}^{-1}$) was simulated for a possible stealth plume under the current detection limits; however, this kind of small-scale plume could be visible to the upcoming space missions. Figure 5 shows the distributions of number density, velocity and column density of this modeled stealth plume. Obviously, it lacked the most distinct features, such as the bow-shape in the upper layer and the bowtie region in the lateral sides, as seen in cases 1–6, with the relatively larger gas production rates due to the insufficient gas collisions. This can be attributed to the cap effect of the canopy shock layer on the plume structure as discussed in [31].

![Figure 5](image-url)

**Figure 5.** (a) Number density distribution (shown in contours with a color scale in units of # m^{-3}). (b) Gas velocity distribution (shown in contour with a color scale in units of m s^{-1}). Gas flow streamlines are presented too. (c) Column density integrated along a line of sight of 90 degrees from Europa’s pole (i.e., perpendicular to the paper). The contour is shown with a color scale in units of # m^{-2}.

Both axes are arbitrary and presented in units of Europa radius.
The observed plume characteristics, such as the gas temperature, gas and dust velocity, dust-to-gas ratio and particulate size distribution, are, in fact, closely related to the subsurface vent conditions [19]. To account for the observed dust size and speed distribution of Enceladus’ plumes, [19] proposed that dust grains are produced from nucleation inside the subsurface vent with water vapor sourced from the interface of liquid water, and wall collisions in the channel determine the grain ejection velocity. In this way, the smaller dust (sub-micron sized) would have an initial velocity exiting from the vent closer to the plume gas velocity. In addition, the width and length of the subsurface channel can control the initial Mach number of the gas plumes and the critical grain size, and the measured gas flux and its dust-to-gas ratio can tell the gas temperature in the subsurface liquid water reservoir. Therefore, our DSMC model simulations, in contrast to the purely ballistic motion consideration, will serve as a useful tool to derive plume properties near surface and the subsurface vent condition.

The plume emplacements can alter surface characteristics such as albedo, color pattern, ice structure and crystallinity (e.g., [54–59]). For example, eruptive emplacements accompanied by cryovolcanism could explain the dark feature material around the linea, lenticulae and ridges [15,16,46]. Ref. [57] also found that irradiated NaCl existed in surface ice of Europa’s leading hemisphere, and its distribution correlated with the disrupted chaos region, consistent with an interior source from subsurface ocean. In addition, some bright areas in the leading hemisphere showing a narrow forward scattering behavior could be indicative of fresh frost deposit due to the plume activity [59]. Moreover, while some regions with relatively higher abundance of crystalline water ice on Europa’s surface could be attributed to a warmer formation environment, such as thermal convection in the ice shell, water outgassing emplacements could account for more amorphous ice found in the polar region [55,60]. Ref. [56] examined Europa surface images collected by the Voyager, Galileo and New Horizons missions, and found no obvious surface pattern change during ~30 years. One of the possibilities, though relatively slim, is that the plume activity and deposit process have reached a steady state. Our simulations show near semi-hemisphere depositions from the large-scale plumes (i.e., with the initial gas bulk velocity in the order of 1.0 km s\(^{-1}\)) and, therefore, the persistence of large outgassing activities may also account for Europa’s young surface and hemispheric color dichotomy. In brief, the plume source region, plume dynamics and emplacements leading to the surface features are closely interlinked. Once information of one or another is brought to light by future observations, it can provide the constraints to the others. For example, knowing the exact source region coupled with the fresh deposit pattern can help constrain the gas emission velocity.

5. Conclusions

In this work, we developed a 3D DSMC model to examine the physical processes and structures of Europa’s hypothetic water plumes with a parametric study regarding the total gas production rate and initial gas bulk velocity. Plume eruption is assumed with expansion from a source region 20 km in radius, which is a reasonable approach to study the large-scale structure of outgassing plumes on Europa using DSMC, though the subsurface vent condition was not well taken care of in our model. The plume characteristics (i.e., the gas number density, gas velocity and temperature distribution) derived from our model can be coupled with the radiative transfer process for multiple-wavelength remote sensing to improve scientific interpretations of the observed spectra and images. The density profiles of the simulated plumes at different altitudes are also provided for comparisons with future measurements.

Our major findings are:

- The gas kinetic temperature rapidly dropped to below 100 K during initial expansion in the low-altitude region (i.e., <100 km) due to the fact of adiabatic cooling;
- Mostly, the central parts of the plumes with large production rates of \(10^{29}\) s\(^{-1}\) and \(10^{30}\) s\(^{-1}\) were in thermal equilibrium and near continuum conditions;
- The gas acceleration near the surface (within an altitude of ~100 km) was a combined effect of gas collision and adiabatic cooling. At a higher altitude, the plume velocity distribution was governed by Europa’s large gravity. The plume simulated from the DSMC modeling (i.e., gas collision considered) was, therefore, generally much larger than the one computed from purely ballistic motion. For example, while the purely ballistic motion of the initial velocity of 0.75 km s\(^{-1}\) could arrive at a maximum altitude of only ~210 km, a similar altitude could be reached by the DSMC modeled plume with the initial velocity of 0.35 km s\(^{-1}\);

- The projection effect could be significant; therefore, it would be not an easy task to trace back a plume to its exact source region on Europa’s surface from the observed 2D images/maps without further supporting information.

Our model inputs of a high gas production rate and large gas bulk velocity producing a large-scale plume, which may be detectable by space- and ground-based telescopes, will cause semi-global deposition of Europa. While the modeling of plume dust deposition was beyond the scope of this paper, it will be studied to investigate the possible surface changes accordingly. The DSMC modeling results will be served as the background gas collision for the dust trajectory integration with a set of dust size and speed distributions. Knowledge of the magnitude, occurrence frequency and source location of the outgassing activity through the follow-up monitoring programs will advance our understanding of Europa’s surface history shaped by plume deposition and erosion due to the fact of space weathering. Finally, the measurements of chemical composition of Europa’s plume material can shed light on its subsurface ocean environment if the outgassing activity can be confirmed to be originated from a subsurface ocean. The yields from the upcoming JUICE and Europa Clipper space missions are highly anticipated to explore this icy ocean world with high potential habitability.

Author Contributions: Conceptualization, W.-L.T., I.-L.L., W.-H.I. and H.-W.H.; Methodology, I.-L.L. and J.-S.W.; Software, I.-L.L. and J.-S.W.; Writing—original draft, W.-L.T.; Writing—review and editing, W.-L.T., I.-L.L., W.-H.I. and H.-W.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially supported by MOST 108-2112-M-003-002 (Physics) and MOST 110-2112-M-008-003. It was also partially funded by the Einstein Young Scholar Fellowship program (MOST 109-2636-M-003-001) and the MOE Yushman Young Scholar program.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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