Callisto's Dynamic Atmosphere

Understanding the Effects of the Jovian Plasma

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1. ABSTRACT

This paper presents an analysis of the atmosphere of Callisto and discusses how the Jovian system molded, and continues to mold Callisto's atmosphere over time. Before the analysis the general properties of Callisto and the atmosphere is reviewed and a literature review of pertinent information regarding the Callisto's atmosphere and previous scientific simulations of the atmosphere. These simulations and observation data for the atmosphere provide a basis for all the parameters used in all of my simulations of the atmosphere. The results of these simulations will provide context on the effect of Jovian plasma on the atmosphere and how the Jovian plasma will continually impact the atmosphere. The source of Callisto's atmosphere and how this source alters over time will also be discussed.

2. INTRODUCTION

Table 1. Callisto General Properties

Parameter	Value
Radius	2410 km
Mass	$1.076 * 10^{23}$ kg
Mean Surface Temperature	135 K
Gravity	$1.24 m/s^2$
Average Semi-Major Axis	$1.88 * 10^6$ km
Average Density	$1.83 g/cm^3$
Orbital Period	16.7 Earth Days
Rotation Period	Tidally Locked
Surface Pressure	$7.5 * 10^{-10}$ kPa
Orbital Speed	$2.953 * 10^4$ km/h

Callisto, with a diameter of 4,800 km, is one of the four large satellites that orbit the gas giant Jupiter and is tidally locked to Jupiter. Callisto is the farthest large satellite from Jupiter, orbiting the gas giant with a mean distance of 1,883,000 km, which is roughly 27 Jupiter radii away from Jupiter. Callisto has the lowest surface gravity of the Galilean moons, about a 10th of Earth's gravity. In addition, Callisto's orbital period is 16.7 Earth days with an orbital speed of 29,530 km per hour. Callisto is not in an orbital resonance with the other Galilean satellites, Io, Europa, and Ganymede, and as a result tidal heating is not a large factor in its development. Callisto has an average density of 1.83 g/cm^3 and has a composition to be roughly 60 percent rocky material and 40 percent ice. The non-icy material on Callisto seems to be made up of magnesium and iron silicates along with sulfur and carbon dioxide. The icy component is thought to be made up of water ice and other more volatile ices although the exact compositions are unknown. Constraints on the overall composition were determined based on the Galileo spacecraft gravity measurements of Callisto, "geochemical constraints on composition of ordinary and carbonaceous chondrites", and the knowledge that Callisto is partially differentiated. The surface of Callisto consists of water ice, ammonia, carbon dioxide, sulfur dioxide, magnesium and iron silicates, and possibly other "unidentified hydrated materials/minerals" which were found via the use of ultraviolet and near-infrared spectroscopy. Callisto's surface is also riddled with areas of darker materials which are composed of non-icy materials found through spectroscopy. By comparing surface temperatures and geological factors, Callisto would be expected to have more volatile ices when compared to Io, but similar to Europa. This is because Io's surface contains mostly sulfur and sulfur oxide in various states due to the tidal forces produced the volcanic activity known to take place on Io. Europa, alternatively, has ice water as well as sulfates that produce the red materials in the fractures on the surface, which is similar to some of the chemical compounds thought to reside on Callisto.

3. GENERAL BACKGROUND

Callisto's atmosphere, while very tenuous, is larger than the atmospheres of the other Galilean moons. Callisto's atmosphere is thought to be composed primarily of O_2, with a surface density of $2*10^{10}$ molecules per cubic centimeter, and CO_2 at roughly $4 * 10^8$ molecules per cubic centimeter. This surface density of O_2 corresponds to a vertical column density of O_2 on Callisto to approximately $2 * 10^{16}$ molecules per cubic centimeter. Similar to any atmosphere on a planetary body, as distance from the planetary body increases the density of the atmosphere decreases. Figure 1, seen below, shows how oxides in Callisto's atmosphere vary as altitude increases. Furthermore, while Callisto's atmosphere is composed of several different gaseous species the primary gas used in atmospheric models of Callisto have focused on molecular oxygen or the combination of molecular oxygen and various carbon species. Moreover, for the model I am constructing, in CFD (Continuum/Computational Fluid Dynamics) and in an analytical model, oxygen will be the only gas to be accounted for due to the major amount it contributes to Callisto's atmosphere.

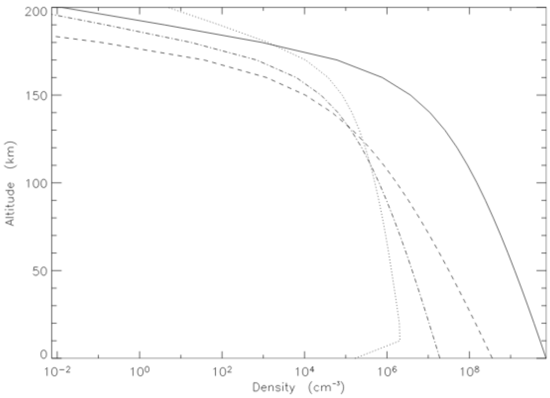


Figure 1. Shown in the image is how the compound abundance varies with altitude on Callisto. O_2 (Solid line), O(dotted line), and CO (dash-dotted line).

Additionally, even though Callisto is tidally locked and the same hemisphere always faces Jupiter, the atmosphere varies based on the satellite's location in orbit. Figure 2 illustrates tidally locked objects and the effect this has on the object.

One major reason for this time variable atmosphere and the more tenuous atmospheres of the other Galilean moons is the Jovian magnetosphere. The strong magnetic field created by Jupiter mostly deflects charged particles from the solar wind. However, the magnetic field also traps ions and electrons which can originate from Jupiter itself, from plasma and meteorite interactions with the Jovian satellites, or from the volcanically active moon Io. The magnetosphere plasma generally moves outward from the planet, and these inhomogeneous sources of material can lead to a large number of charged particles which diffuse throughout the Jovian magnetosphere, from Io to Callisto, and subsequently effect Callisto's surface and the overall atmospheric composition. The portion of the Jovian plasma around Callisto's location is sulfur ions, with a number density of $3.4 * 10^{-2}$ particles per cubic centimeter, originate at the sulfur volcanoes on the surface of Io. The rest of the Jovian plasma is made up of oxygen ions, sodium ions, hydrogen and helium ions, $8.87 * 10^{-3}$, $2.29 * 10^{-3}$ and $4.94 * 10^{-6}$ particles per cubic centimeter respectively. The values that were calculated, except for the hydrogen values, are within the ranges of ion densities outlined in the Vorburger and Wurz (2015) Monte-Carlo simulation paper as seen below.

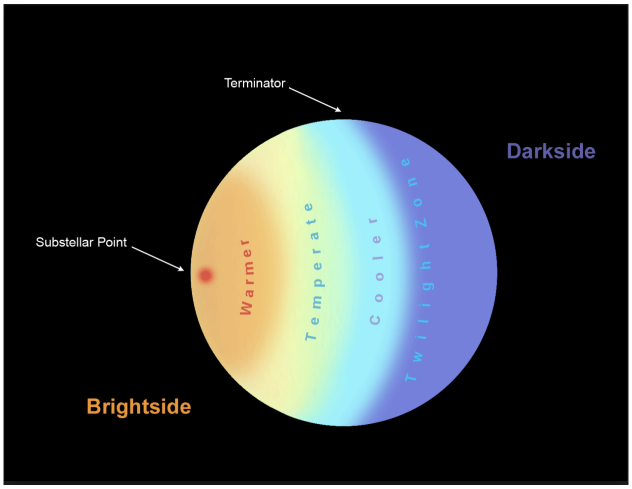
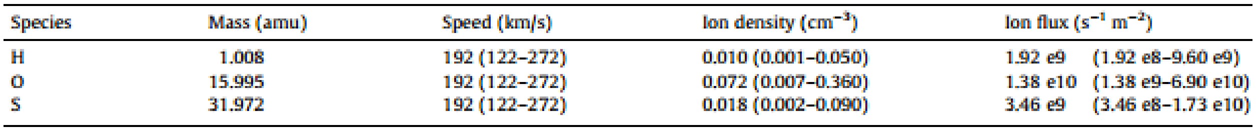


Figure 2. The figure above shows the temperature distribution of a tidally locked object. Locations of high temperature correspond to the day side and low temperatures the night side. Regarding Callisto, one side of the planet always faces Jupiter. Diagram from BackAlleyAstronomy

4. LITERATURE REVIEW

Initially, the ion concentrations were calculated using the model outlined in the Divine and Garrett (1983) paper on the charged particle distributions in the Jovian magnetosphere. Divine and Garrett (1983) uses a series of equations and variables to determine the $O+, H+, He+$, and other ion densities at various distances with respect to Jupiter. These equations and computed densities are discussed in more detail in Divine and Garrett (1983). The entire process involves a coordinate system with respect to Jupiter and with respect to the satellite/location used to calculate the plasma.

There are a couple of ways that the Jovian plasma can affect Callisto's atmosphere. For example, particles hitting the icy surface of Callisto can



Species	Mass (amu)	Speed (km/s)	Ion density (cm^{-3})	Ion flux (s^{-1} m^{-2})
H	1.008	192 (122–272)	0.010 (0.001–0.050)	1.92 e9 (1.92 e8–9.60 e9)
O	15.995	192 (122–272)	0.072 (0.007–0.360)	1.38 e10 (1.38 e9–6.90 e10)
S	31.972	192 (122–272)	0.018 (0.002–0.090)	3.46 e9 (3.46 e8–1.73 e10)

Figure 3. Shown is a table of the relative ion abundances around Callisto's exosphere.

cause the ice to become dislodged from its initial crystalline structure. Direct removal of molecular and atomic species due to ion irradiation of the surface is known as sputtering. Alternatively, breaking and reforming of molecular bonds can cause volatile molecules such as O_2 to form and these will then escape into the atmosphere. Sputtered particles, as well as other particles in the atmosphere, can fully escape a satellite depending on the characteristics of the satellite's atmosphere, the gravitational pull of the satellite, and the particle's kinetic energy. For example, if a molecule is ejected with a low energy relative to the escape energy on a satellite with very little atmosphere the molecule will travel on a ballistic trajectory and return to the surface of the satellite. While in orbit the molecule does contribute to the atmospheric corona on the satellite. If the molecule is ejected from the surface of a satellite with a substantial atmosphere, the molecule can join with the atmosphere, potentially interact with the atmospheric molecules, before it eventually falls back to the surface. Furthermore, because of the magnetospheric plasma surrounding the Jovian satellites, molecules that become ejected from the surface can interact with the charged particles, and which can be driven back to the surface which can enhance the overall sputtering rate.

The process of plasma impacting, and re-impacting, the exobase, outermost region of an object's atmosphere where the mean free path of particles is greater than the scale height, of a satellite can also increase the amount of atmosphere lost through energetic molecules increasing the energy of molecules it collides with in the atmosphere. As discussed above, the energy of a molecule is one of variables that can assist the observer in determining what will happen to that molecule given a series of events. There are two major factors that contribute to the energy of a molecule, which helps determine whether the molecule will escape the satellite or not, which is the gravity of the satellite and the thermal stimulation. While gravity acts as a barrier that stops molecules with large masses from escaping the atmosphere, thermal stimulation, photon heating, needs to also be considered. Jeans escape, the term used to describe the mechanism of a thermal escape of an object's atmosphere, which considers a molecules average kinetic energy as well as other thermal stimulation that can bring its kinetic energy above a specific threshold. This mechanism of escape is important to consider because the total energy of a particle is not solely determined by its speed but can also be influenced by temperature increases that could result from various processes.

Wolf and Mendis (1983) use estimates of the parameters of the Galilean satellites to reason how the Galilean satellites will be affected by the variable Jovian plasma. Wolf and Mendis (1983) reason on how and why the atmosphere of the Galilean moons is observable, and the effects of plasma bombardment on the surface is relatively limited in scope due to the complexity of the interactions. Furthermore, Wolf and Mendis (1983) discuss how the ionosphere of each satellite could be swept away based on the variable Jovian plasma. The magnitude of the plasma is varies based on the orbital position of each of the satellites.

A large abundance of gas molecules in the atmosphere can help prevent low energy plasma from reaching the surface of the moon. On the other hand, a tenuous ionosphere could be swept away by the Jovian magnetosphere if the total ion production rate were less than the flux of the incoming plasma. An ionosphere lays above the atmosphere and contains a high concentration of ions and free electrons. This physical phenomenon is likely to occur when the mean free path of the particles is less than the scale height of the atmosphere. This relationship, taken from the Wolf and Mendis (1983) on the icy moon interactions with the Jovian plasma, can also be seen mathematically below:

$$q(h) * H < n(h) * V \tag{1}$$

q(h) describes the ion production rate of the satellite's ionosphere as a function of height, in units of number of ions per cm^3 s, H is the scale height of the ionosphere while n(h) is the number density of the magnetospheric particles at a given height, h, and V is the convective velocity of the magnetospheric particles relative to the satellite.

Because scale height, the density of magnetospheric particles (based on the assumption that the Jovian plasma only changes with horizontal distance from Jupiter we are ignoring smaller differences that could vary based on height from the satellite's surface because the magnetosphere is non-uniform) and the convective velocity, are basically constant the only dynamic variable is q. As a result, the Wolf and Mendis (1983) paper calculates the lower limit of the total ion production rate, which means for an atmosphere to not get swept away by the Jovian magnetospheric plasma the atmosphere would have to produce more ions per second than the calculated values. For Callisto, $q \geq 0.5cm^{-3}s^{-1}$ while for Europa, $q \geq 15cm^{-3}s^{-1}$. Europa's ion production rate needing to be 30 times larger than Callisto can be explained by the fact that the density of the magnetospheric particles around Europa is much greater than around Callisto. Furthermore, even though Callisto has a higher scale height, 45 km compared to 37 km, and a greater convective velocity, $192kms^{-1}$ compared to $87kms^{-1}$ the Jovian plasma densities have a greater difference between the two satellites which causes the q value to increase greatly for Europa. Wolf and Mendis (1983) conclude the ionosphere of Callisto would be swept away due to these parameters.

The atmospheric model of Callisto has been recently modeled by Vorburger and Wurz (2015) which builds on the atmospheric model work done on Carlson (1999), Strobel (2002), Kliore (2002) and other researchers that have used observed data from the Galilean spacecraft along with simulations to model Callisto's atmosphere. In the Vorburger and Wurz model the group first assumes that Callisto's exosphere is collision-less even though observational data, in Cunningham (2015), on Callisto's O_2 column density, is measured to be approximately $4*10^{15}cm^2$ on the leading hemisphere, shows that Callisto's atmosphere is actually collisional. Secondly, the Vorburger (2015) model splits Callisto's atmosphere into input processes and lost processes that have non-negligible effects on the atmosphere. The input processes that the model considers are ion induced sputtering, sublimation, and photon-stimulated desorption while the loss processes that the model is concerned with are gravitational escape, ionization, and surface adsorption. Regarding input processes, the model takes into account O^{n+}, S^{n+}, and H^+ ions with ion fluxes of approximately $1.92 * 10^{10}m^{-2}s^{-1}$ with speeds of, roughly, 192 km/s which was taken from Kivelson (2007). Their Monte-Carlo model considers both mineral sputter yields as well as ice sputter yields and the aftermath of the ejected particles. This Monte-Carlo model provides sputtering yields for the night side of Callisto and the day side to account for the variation of ice sputter yields with respect to temperature. The sublimated flux of Callisto is a function of Callisto's surface temperature which ranges between 80 K and 160 K with ice H_2O controlling the sublimation from of the many elemental species embedded in the icy surface. Finally, photon simulated desorption while important for objects closer to the sun, its importance decreases with increased distance for the sun. Photon simulated desorption considered even though it is not a major of a contributor, it releases particles with velocities higher than normal thermal release. On the other hand, the photo ionization rate, which also scales with distance from the sun, on Callisto is between 10^{-8} to 10^{-10} s^{-1} depending on the elemental species. The incident magnetosphere plasma contributes electrons that also increase the overall ionization on the moon and as a result the electron ionization rates on Callisto are roughly $10^{-9}s^{-1}$.

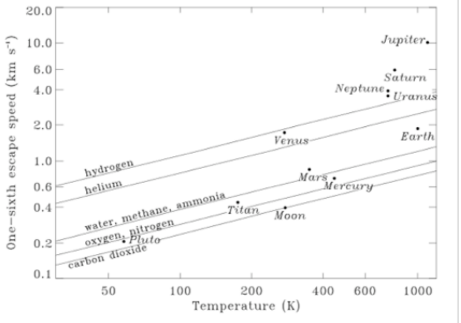


Figure 4. Shows how elements/compounds escape based on the values of different parameters such as molecular weight and temperature.

An improvement on the, comprehensive, Vorburger (2015) model, would be to examine the differences between the structure of a collisional and non-collisional atmosphere. Callisto's atmosphere varies between collisional and non-collisional based on the surface temperature and flux of plasma impacting the atmosphere. By such a comparison I can determine whether collisions in the atmosphere affect the atmospheric density and temperature significantly. A comparison between two atmospheric types can be explored through a modified molecular kinetic model called the Direct Simulation

Monte Carlo (DSMC) model as compared to the Vorburger collision-less Monte Carlo model. The model I will be using is less comprehensive than the Vorburger model due to computation limits but will model a collisional atmosphere. Furthermore, my model does not account for the surface sputtering or Callisto's day-night side atmospheric asymmetry. The current version of my DSMC model of Callisto's exobase accounts for magnetospheric particles, in the form of $O+$ ions, causing atmospheric sputtering. One of the primary reasons for using this simplified model of Callisto's atmosphere with respect to the Jovian system is to understand how the magnetospheric plasma degrades Callisto's atmosphere.

5. COMPARISON OF CALLISTO AND EUROPA

Comparing Callisto's atmospheric properties to those of the other Galilean moons will assist in providing further insight into the effect of the Jovian plasma on atmospheric properties. Callisto's atmosphere has been discovered to be a mixture of carbon dioxide and molecular oxygen while Europa's atmosphere has been observed to have an even more tenuous atmosphere that is mostly made of molecular oxygen. This is a result of Europa being extremely closer to Jupiter than Callisto, 9.4 Jupiter radii vs 26.6 Jupiter radii, and as a result the Jovian plasma is more abundant the closer one gets to Jupiter. This is confirmed by the calculations done using the model found in Divine and Garrett (1983) paper which show the number density of charged particles around 9.4 Jupiter radii to be, roughly, 300 times greater than the number density of the plasma at Callisto's location. Using information based on the location and the increased flux of charged particles, it is known that Europa's tenuous molecular oxygen "surface bound" atmosphere formed primarily is through the sputtering of Jovian plasma of its icy surface. The chemical reactions between the ion radiation and ice cause molecular oxygen to be produced and escape into the atmosphere. Due to the known composition of Callisto's atmosphere it is known that Callisto's O_2 portion of its atmosphere could have formed in a similar process as Europa's. As stated previously, the Jovian plasma also will efficiently strip away the atmosphere at Europa while increasing the sputter yield of Europa which explains the more molecular oxygen atmosphere at Callisto. The escape energies of Europa and Callisto are relatively close together, 0.021 and 0.031 eV/u, with the escape velocities being 2.025 km/s and 2.440 km/s, respectively. Furthermore, figure 4 from NASA Star Gaze FAQ relates escape velocity to exobase temperature and assists in showing when Jean's escape is an important factor to consider for certain elements.

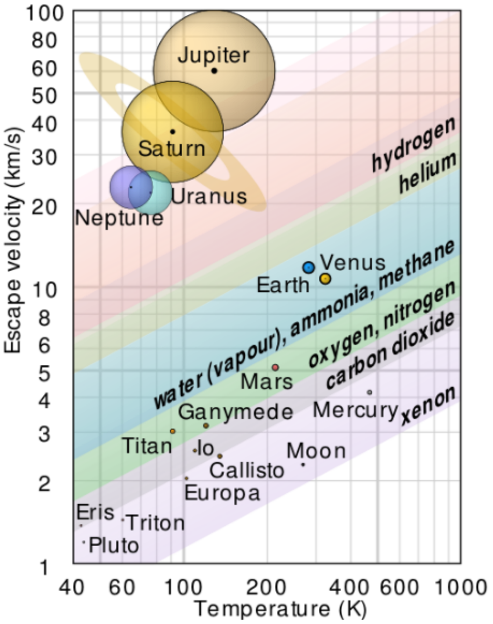


Figure 5. Illustrates how exobase temperature and element type impacts the escape velocity. Callisto and Europa are both shown in the graphic.

The exobase temperatures of Europa and Callisto are roughly 100 and 130 K which explains why hydrogen and helium will escape from both satellites because both elements are far outside the acceptable range, indicated on figure 4. Furthermore, based on the chart, water, ammonia, methane, oxygen, and carbon dioxide should all undergo Jean's escape from both Callisto and Europa. This is easily inferred from Fig. 4 if one takes the escape velocity and the surface temperature of a celestial object and finds that intersection point on Fig. 4. The elements above that point represent elements that would escape that satellite's environment while elements below the point would not escape. This conclusion reinforces the atmospheric composition of Europa, with a primarily O_2 atmosphere, but is not consistent with the fact that Callisto has an observationally confirmed carbon dioxide atmosphere, which was discovered via the Galileo spacecraft in 1997.

One potential reason on Callisto's tenuous CO_2 atmosphere is that the CO_2 on the surface sublimates which replenishes the CO_2 when it escapes. Without a source of CO_2 to continually replenish the atmosphere there would not be CO_2 gas on Callisto. Additionally, the O_2 in both Callisto's and Europa's atmospheres would need a source because O_2 is lighter than CO_2, as seen in Fig. 3, and therefore should escape even faster than CO_2. The major source of O_2 in these satellites is the sputtering of ice H_2O on the surface of these satellites by the energetic particles in the Jovian magnetosphere that make it to the moon's surface. The atmospheres of both Europa and Callisto are determined by the total loss rate vs the total source rate.

6. CALLISTO ATMOSPHERIC MODELS

I will begin by providing an overview of the computational work I have done to model Callisto's atmosphere. Afterwards, I will provide an analysis of the parameters/values generated by these models. For modeling Callisto's atmosphere I, initially, attempted to use Computational Fluid Dynamics (CFD) model. The plan was to use the steady state solution for Callisto's lower atmosphere and use the parameters generated from the CFD model to create a DSMC model. Additional work using the CFD model illustrated the limitations of the software. This model was eventually deemed inadequate to correctly model Callisto's tenuous atmosphere. A DSMC simulation code was then utilized to model multiple variations of Callisto's atmosphere. The initial simulations were basic in structure, a single element atmosphere, but grew in complexity once the results generated appeared to be reasonable. The same DSMC simulation code is being utilized to analyze the multi-species atmosphere of Callisto.

6.1. *CFD Model*

CFD models work by solving the fluid equations based on the boundary conditions and properties of the system. CFD has default material properties to choose from or materials can be developed by inputting properties such as the density, yield strength, and various other properties. Once material properties have been set to each aspect of the system, one has to apply boundary conditions to the surfaces/edges/faces of the system. Potential boundary conditions can range from flow rates to pressure to temperature. Boundary conditions assist in driving the flow and modeling the correct behavior of the system. The results of the CFD model depend heavily on the boundary conditions associated with the model. Once the boundary conditions are set, a mesh is set to the entire model and then the simulation is ready to be run. The mesh size is variable and can be refined.

Two CFD models were developed to model Callisto's atmosphere. The first model was a 3D, cylinder shaped model. Due to the shape of the 3D model, the boundary conditions for the CFD can only be applied on surfaces. Therefore, the location of boundary conditions is based on the orientation of the surfaces outlined in figure 5. Illustrated in figure 5, the center of the cylinder represents the moon of Callisto and the surrounding medium represents the atmosphere of the moon. The material associated with this atmosphere in CFD is molecular oxygen. The input parameters of temperature, density, and pressure have been modified to represent Callisto's temperature, pressure and density. Furthermore, the altitudes are from 0 km (the surface of Callisto) to 120 km above the surface. The boundary conditions for the CFD simulation are as follows:

Lower Surface Boundary Condition

- Absolute Pressure (P_0) = $7.5 * 10^{-10} kpa$
- Temperature = $135K$

Upper Surface Boundary Condition (120 km)

- Absolute Pressure = $7.5 * 10^{-12} kpa$

General Conditions

- Hydrostatic Pressure Enabled (Using Callisto's value of gravity in -y direction)
- Total Altitude = $120km$
- Scale Height = $30km$

The surface temperature and pressure values were taken from previous literature and observational data on Callisto. The upper absolute pressure was computed using the scale height of Callisto's atmosphere. The scale height used above was computed using the approximation below:

$$H = \frac{R * T}{g} \tag{2}$$

H is the scale height, T is the mean surface temperature (135 K), R is the specific gas constant for oxygen ($259.8J * kg^{-1} * K^{-1}$), and g is the gravity on Callisto ($1.24m * s^{-1}$). For a multi-species atmosphere this value was recalculated.

Using these conditions the static atmosphere of Callisto was modeled and the results for the CFD simulations are shown in the graphical figures below. The purpose of the 3D and 2D CFD simulations were to approximately model the collisional aspects of Callisto's atmosphere. The 3D model was initially constructed, however was converted into a 2D model because of an unintended pressure distribution occurring along the outer surface of the CFD model. The figures below illustrate the pressure and density variation along the height of the 3D CFD simulation. The 3D CFD simulation does approximate the behavior of atmospheric variation with altitude.

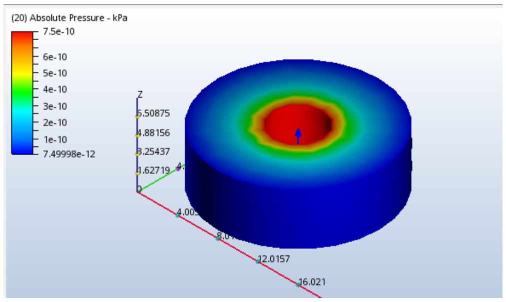


Figure 6. Illustrates the pressure variation along a 3D simulation of Callisto's atmosphere. The atmosphere in this simulation is composed purely of molecular oxygen.

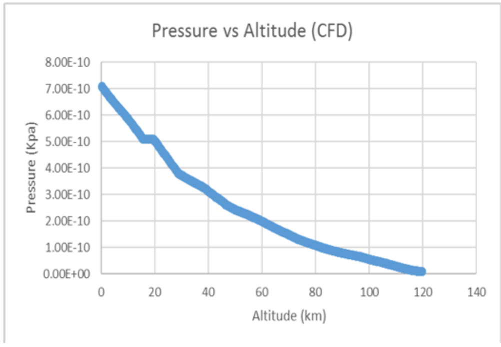


Figure 7. Illustrates the pressure variation along a 3D simulation of Callisto's atmosphere. The atmosphere in this simulation is composed purely of molecular oxygen.

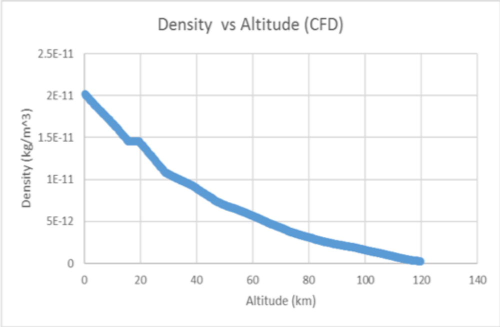


Figure 8. Illustrates the pressure variation along a 3D simulation of Callisto's atmosphere. The atmosphere in this simulation is composed purely of molecular oxygen.

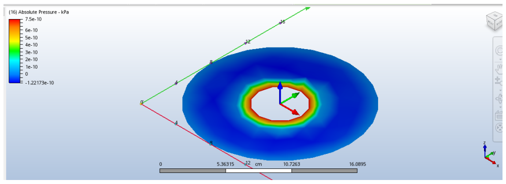


Figure 9. Shows the pressure variation in the 2D CFD simulation used to model the static atmosphere of Callisto. This variation of the CFD simulation assumes an atmosphere composed purely of molecular oxygen.

The 2D CFD simulation results are shown in Figure 8 and the atmospheric properties vary with altitude are also seen in the figures below. This particular model was computationally less intensive than the 3-D model and produced similar results for the variation of pressure variation with altitude. Furthermore, the 2D simulation lacked the secondary pressure variation in the z-axis because of the nature of the simulation.

While there was success with the CFD simulations I was able to create, the scope of these simulations were limited. The original simulations constructed were static in nature and failed to represent the dynamic nature of Callisto's atmosphere. The CFD software used to create the initial simulations could support transient simulations, the materials library and boundary condition manipulation were very constrictive. The material library did not have the atomic compounds necessary to accurately represent Callisto's atmosphere should more complex simulations be run. Furthermore, the original 2D and 3D models contained boundary conditions that forced certain surfaces to be specific pressures and did not allow the pressure to naturally approach 0 over as distance from the surface of Callisto approached infinity. CFD did not support the modeling of atmospheric stripping or sputtering due to nearby particles. Additionally, Callisto has a tenuous atmosphere that borders between fluid and non-fluid based on the time or altitude. As a result, the CFD simulations being run would only be relevant for a select portion of Callisto's atmosphere and the results could only be discussed based on these fluid regions of the atmosphere. Due to these above reasons, the fluid models of Callisto's atmosphere were tabled for a particle model. This was seen to be more robust than the DSMC and the results more relevant to the aspects of Callisto's atmosphere that have studied the least. A direct simulation Monte Carlo (DSMC) was written by a fellow colleague for the study of the Martian atmosphere and I adapted said code for Callisto.

6.2. *DSMC Models*

The DSMC code is a complex code with a variety of parameters and options associated with it. The general code works by dividing the specified range of distance into a number of cells, specified by the user. The user also specifies the number of particles in the simulation, the type of particles,whether there are different types of particles in the atmosphere and the method of initially importing these particles. The properties of the planet/moon are also required to properly construct the atmosphere being modeled. Input information from the density of the object to the object's scale height and surface gravity are all required inputs. The user also specifies the range of time to simulate the atmosphere and the time step. Finally, the DSMC can simulate atmospheric sputtering and the user can define the type of particles, and number of particles, impacting the atmosphere. The user also specifies the collision type used to calculate the transmission of energy from one particle to another. Once the required parameters are specified, the simulation can be run and the code outputs a data files that detail the density,temperature, velocity, and location of every particle in the simulation at every time step interval and recalculates them.

The DSMC code for Callisto's atmosphere required multiple input parameters and can simulate tenuous atmospheres more accurately than the CFD model. Input parameters vary from the surface temperature, surface pressure, number of species in the atmosphere to whether atmospheric sputtering occurs, the specific ions impacting the atmosphere, and the kinetic energy associated with these. Due to uncertainty with the DSMC model's ability to correctly model a multi-species atmosphere that is continually impacted by ionized magnetospheric particles, the initial simulations of the atmosphere are simplistic in nature. Initial simulations mirror those of the CFD model and the results are analyzed. Further level of complexities are added to the DSMC model such as additional species or atmospheric sputtering by 1 type of ionized particle.

Initially, a O_2 DSMC with parameters similar to the input parameters of the CFD method were used to study the agreement between the two models. The same surface pressure, the same total height of the simulation and the same surface temperature. The initial run of the DSMC code involves a purely O_2 atmosphere, without taking into account atmospheric sputtering due to ionized particles. The figures below outline the results obtained from the O_2 run of the DSMC simulation of Callisto's atmosphere. The multiple lines relate to the each particle in the simulation and the graphs in total illustrate the each particle's development over time within the simulation. As shown in figure 11, the mass density of the atmosphere varies with altitude in a manner similar to the density plots from the CFD model. The DSMC simulation, however, initially showed a strong uncertainty in the temperature values as altitude increased. Several particles, in the temperature graph, have a higher range of oscillations than others. Furthermore, all of these oscillations increase as altitude increases. This could illustrate particles at higher altitudes have more thermal energy and thus are closer to escaping the atmosphere.

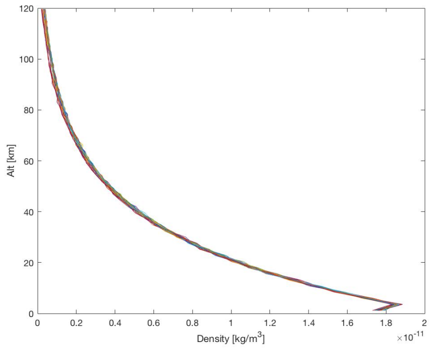


Figure 10. Shows the mass density variation as altitude increases for the purely O_2 atmosphere from the DSMC simulation.

After analyzing these results, several parameters were altered for the next iteration of the DSMC code. Atmospheric sputtering due to ionized $O+$ was implemented. I used the ion flux value for $O+$ found in the Vorburger and Wuz (2015) and computed the average energy of an $O+$ ion using the

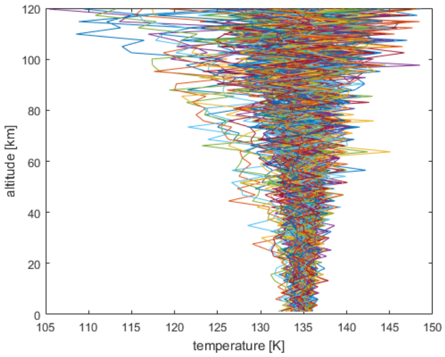


Figure 11. Shows the temperature variation as altitude increases for each particle for the purely O_2 atmosphere from the DSMC simulation.

average velocity outlined in that paper. The table in which the values were taken are in figure 1. The equation I used to find the kinetic energy of the O+ ions around the exosphere of Callisto is:

$$K = \frac{1}{2} * m * v^2 \tag{3}$$

M being the mass of an $O+$ ion ($16*1.67*10^{-27}$) in kilograms and v is the velocity in meters per second.

Ionized $O+$ was implemented due to how close in molecular weight ionized $O+$ is to O_2.Therefore, the collisions between the two species were expected to yield reasonable results due to the small mass differential. Collisions between molecules of vastly different masses has been untested by this particular iteration of the DSMC code. The collisions between the the ionized $O+$ and O_2 were modeled using the hard sphere approximation for ease of calculation. Figure 13 shows the mass-density as a function of altitude and illustrates there is no visual difference between this figure and the figure outlining the same property without the atmospheric sputtering.

The figures shown illustrate adding atmospheric sputtering, initially, does not seem to change the basic properties of the model, being the pressure distribution and temperature variation. However, the average velocity of the particles in the atmosphere proves to be interesting due to the impacting ionized particles. Figure 14 shows the magnitude of velocity of each particle and several particles/regions of higher velocity. Additionally, the temperature distribution shows higher temperature values at upper altitudes. The impacting ionized particles' influence can be seen in these regions of

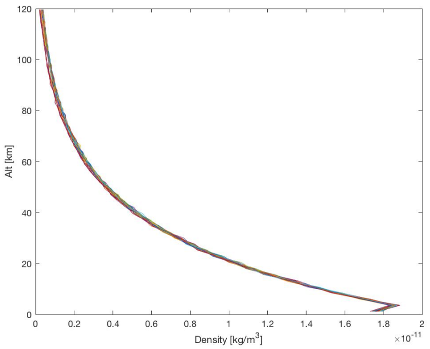


Figure 12. Shows the mass density variation as altitude increases for the purely O_2 atmosphere with atmospheric sputtering via ionized O from the DSMC simulation.

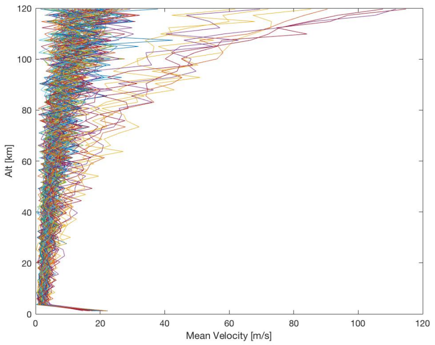


Figure 13. Shows the magnitude of velocity of particles in the O_2 atmosphere from the DSMC simulation. This velocity for each particle is calculated by summing the velocity components of the particle in each dimension. This graphical result is based on the simulation involved with atmospheric sputtering

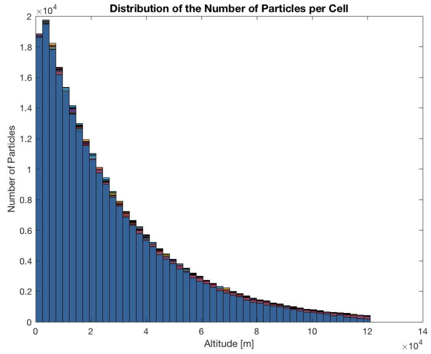


Figure 14. Shows number of particles per bin in the DSMC simulation of the O_2 atmosphere. Used as a reference to see the number of particles in the atmosphere as the altitude increased.

increased velocity or temperature. These collisions transfer energy from the moving charged particles to the relatively stationary atmospheric particles and could even eject these particles from the atmosphere, leading to atmospheric decay over time.

The histogram shown in figure 14 outlines the number of particles in each bin and the number of bins vs altitude of the simulation. This was used to determine the number of particles towards the upper regions of the atmosphere and whether the need to add more particles into the simulation was needed. Due to the region of most interest being the upper regions of the atmosphere, and the lack of particles in that region, more particles were added into the next runs of the simulation. Improving the accuracy of the behavior of escaping particles due to atmospheric sputtering is the main study objective of the DSMC simulations.

For the next use of the software, multiple parameters were altered to adjust for the results of the previous simulations and to model the DSMC simulations completed in the Vorburger (2015). The max altitude was increased from 120 km to 5500 km, the number of particles in the simulation were nearly doubled from the previous iterations, and carbon dioxide (CO_2) was added as an active species in the atmosphere. Increasing the maximum altitude of the simulation this much was because it was suggested that the particles could be escaping at an altitude higher than 120 km and the previous simulations have been unable to show this behavior because of the limited altitude range. Furthermore, Vorburger (2015) also details using DSMC to model the atmosphere with the maximum altitude being around 5000 km.

7. FUTURE WORK AND POTENTIAL IMPACT

Future work on this project would involve developing a transient simulation to approximate how Callisto's atmosphere changed due to the atmospheric sputtering by charged particles from the Jovian magnetosphere impacting Callisto's atmosphere over time. Completing the current DSMC simulation to work with multi-species atmospheres and multi-species ions will contribute greatly in estimating the decay rate of Callisto's atmosphere. Additionally, simulations of Callisto's atmosphere which closely resemble the observed parameters of CO_2, O_2, and other prominent compounds will provide further insight on how much material is escaping from Callisto's gravitational influence.

With the announcement of the JUICE (Jupiter Icy Moons Explorer) mission to the Jovian system, useful atmospheric models, and other models regarding different processes in the system, are extremely important on determining how much time is spent on each moon and what data researchers should expect. The mission is planned to launch in 2022 and is set to arrive at Jupiter in 2030, it will spend at least three years collecting data around Jupiter and Ganymede, Callisto and Europa. New data gathered from this new model of Callisto's atmosphere with context on how this atmosphere evolved other time will provide insight on exactly how the Jovian system itself evolved over time. This is due to the fact that the atmospheres of all the Galilean satellites are heavily dependent on the variable Jovian plasma that impacts each satellite, as previously mentioned in detail above. Therefore, one can assume that the evolution of Callisto's atmosphere, as well as the other Galilean moons, is due, primarily, to the evolution of the Jovian plasma, or Jupiter itself.

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