THE EFFECT OF JUPITER'S EARLY LUMINOSITY ON THE GALILEAN SATELLITES.

C. J. Bierson[1], J. J. Fortney[2], K. T. Trinh[1], and M. Kreslavsky[3], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA (CBierson@asu.edu), [2]Astronomy and Astrophysics Department, University of California Santa Cruz, Santa Cruz, CA, USA, [3]Earth and Planetary Sciences Department, University of California Santa Cruz, Santa Cruz, CA, USA,

Introduction: After its formation, Jupiter is estimated to have been ten-thousand times more luminous than it is today. At this time, the inner satellites Io and Europa would have received an order of magnitude larger incoming flux from Jupiter, than solar insolation. In this work we explore the implications of this early heating on the inner Jovian satellites.

In the last stages of Jupiter's formation it accreted gas from a local disk of material. The large Galilean satellites were forming within this disk [1]. For this work, we consider what occurs after this disk dissipates. We assume that at this point the satellites have finished accreting and Jupiter is cooling from it's initial luminosity.

The magnitude of Jupiter's initial luminosity depends on its initial entropy and is therefore sensitive to the details of Jupiter's formation. This leads to a nearly order of magnitude uncertainty in Jupiter's initial luminosity at the end of accretion [2, 3]. Taking a typical value of 10^{-5} $L_{\odot}$, where $L_{\odot}$ is the current solar luminosity, the satellites Io, Europa, and Ganymede would receive 30, 10, and 3 times more heating from Jupiter than the Sun respectively.

The clearest impact this initial heating may have had on the early satellites would be in the form of volatile loss. The Galilean satellites have a clear trend in composition from the rocky Io close to Jupiter to the outer icy Ganymede and Callisto [4]. Past works have proposed a number of possible pathways for this compositional gradient to form, each with their own merits and weaknesses [5-8]. For the purposes of this abstract, we consider what may have occurred if a significant amount of ice was present on Io after its accretion.

Methods: In this work we use an energy balance approach to model the surface temperature of the Galilean satellites. We follow the approach of Lehmer et al. [9] with an added term for the heating from Jupiter. When the surface temperature exceeds the melting point of water a surface ocean can form. In this case a water vapor atmosphere will also form in equilibrium with the ocean. Our modeling accounts for the greenhouse heating this atmosphere can cause. Under these conditions rapid atmospheric loss can occur via hydrodynamic escape.

Hydrodynamic escape is a mechanism of atmospheric loss wherein there is a radial wind driven by the pressure gradient between the surface and background of space. This mechanism is particularly efficient in cases of high heating and low gravity, as is the case for the inner satellites heated by the young Jupiter.

For the specific values of Jupiter's luminosity history we use the model of Fortney et al. [10]. This model smoothly and monotonically transitions from a high initial luminosity to the modern value. Because of this we can treat our uncertainty in Jupiter's initial luminosity as an uncertainty in the start time of our model. We have also used the alternative Jovian luminosity model of D'Angelo et al. [11] and find our results are unaffected by the model choice.

For this work we use the satellites current orbital distances from Jupiter. The Galilean satellites are expected to have migrated away from Jupiter over solar system history due to tidal forces [12]. Therefore we expect our results to somewhat underestimate the local flux at each satellite.

Results: We find that during the first few million years after its formation, Io could have had equilibrium temperatures in excess of 300 K due to Jovian radiation. With greenhouse heating, this energy flux is sufficient to remove a quantity of ice equal to Ganymede's current inventory.

For Europa we find that surface temperatures may be near 270 K initially and fall rapidly. We only predict significant mass loss if Jupiter's initial luminosity was in excess of 10^{-5} $L_{\odot}$ for an extended period of time or Europa was significantly closer to Jupiter during this early period.

In our model Ganymede does not reach temperatures above 250 K for expected Jovian luminosity values. For the first few million years Ganymede may have had higher surface temperatures, possibly impacting the surface rheology, but we do not expect there would be significant mass loss.

Discussion: The volatile inventories we see at the Galilean satellite today could be the result of one strong process, or many acting in concert. In this work we find that heating from Jupiter could have removed any water inventory at Io in its first few million years if it was present. This could potentially include water from silicates dehydrated by tidal heating. Overall we show that this is a process that should be considered when others struggle to explain the observed density gradient [7].

One potentially important factor not included in this work is that the moon would quickly become tidally locked to Jupiter. In this case there would be strong nearside to farside temperature gradients. More detailed and higher dimensional modeling would be needed to properly account for these effects.

Here we explore this process as it relates to Jupiter but the same physical process could be important for large exoplanets with close in satellites. Given this, ice rich satellites would be unlikely to be in tight orbits to large exoplanets regardless of host star distance.

References: [1] Canup, R. M. and Ward, W. R. (2002) *AJ*, 124, 3404 [2] Marley, M. S. et al. (2007) *ApJ*, 655, 541 [3] Berardo, D. et al. (2017) *ApJ*, 834, 149 [4] Schubert et al. (2004) *Jupiter*, 281 [5] Dwyer et al. (2013) *Icarus*, 225, 390 [6] Ronnet et al. (2017) *ApJ*, 845, 92 [7] Madeira, G. et al. (2021) *MNRAS*, 504, 1854 [8] Bierson, C. J. and Nimmo, F. N. (2020) *ApJ*, 897 [9] Lehmer, O. R. et al. (2017) *ApJ*, 839, 32 [10] Fortney, J. J. et al. (2011) *ApJ*, 729, 32 [11] D’Angelo, G. et al. (2021) *Icarus*, 355, 114087 [12] Hussmann, H., and Spohn, T. (2004), *Icarus*, 171, 391

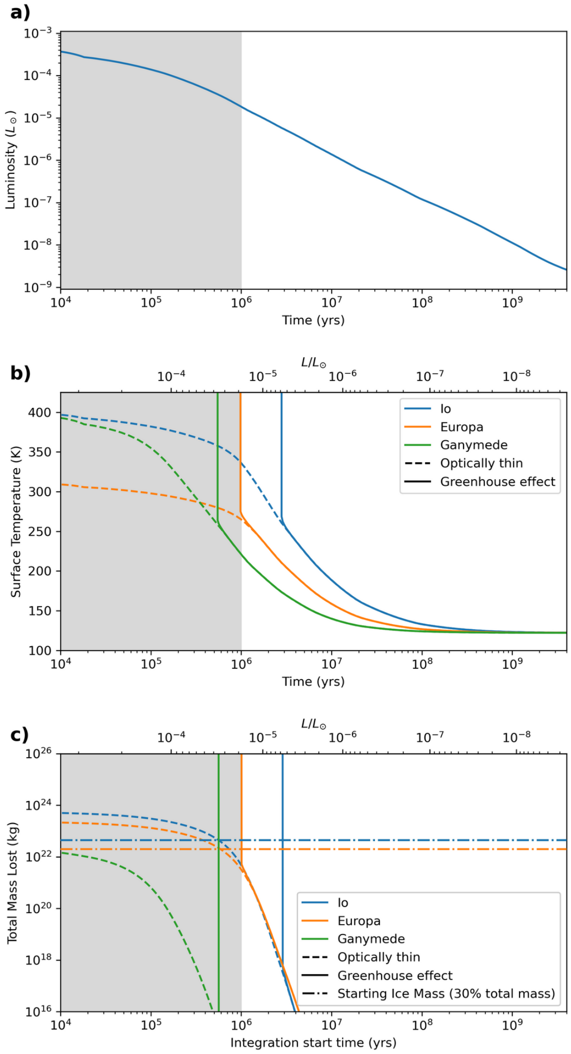

Figure 1: Radiation from Jupiter may have caused significant mass loss on Io and Europa shortly after formation. In all panels times prior to 1 Myr are shaded grey as these luminosity values are not considered plausible. (a) Jupiter’s luminosity (units of solar luminosity) as a function of time [10]. (b) Equilibrium surface temperatures for each of the satellites given the instantaneous Jovian luminosity. Inclusion of greenhouse can cause surface temperatures to not converge for T >300 K [9]. (c) Total water mass lost via atmospheric loss as a function of the assumed starting time. If greenhouse heating is included, more than 30% of Io’s current mass could be lost in the first few million years.