THE ICY ORIGINS OF THE MARTIAN MOONS.

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Introduction: The origins of the Martian moons, Phobos and Deimos, are still heavily debated. There are currently two leading theories surrounding their origin: giant impact or asteroid capture. The asteroid capture theory stems from the moons' irregular shapes, similar to asteroids and other small solar system bodies. Their reflectance spectra also slightly matches known meteorites' spectra, like Tagish Lake, a D-type asteroid analogue, and Murchison, a CM chondrite [1]. Their albedos are around 0.07 and 0.08 for Phobos and Deimos, respectively, similar to the range for C-type asteroids. Along with these measurements, the moons' proposed densities, 1900 and 1750 kg/m^3 for Phobos and Deimos, respectively, are less than the density of silicate (2.5~3.5 g/cm^3), suggesting the moons are composed of hydrated chondrites and/or water ice to account for the lower densities [2]. While asteroid capture theory can only explain their observed physical characteristics, the giant impact theory can only explain the moons' orbital characteristics. It is extremely difficult, however, to capture two objects into the orbits that the moons are currently in, and there is not enough tidal dissipation to move them into their current orbits [2]. Previous giant impact studies can create an impact-generated disk large enough to recreate the moons in their current positions, but this large disk also creates a massive moon within Phobos' orbit, which later would need to fall back to Mars [3][4][5]. Previous impact studies also use an undifferentiated basalt impactor, which causes disk temperatures rise to around 2000 degrees C, melting the disk materials, which would alter or destroy primitive chondritic materials in the impactor [6]. This study proposes the use of an impactor containing mostly water-ice for the following three reasons: (1) that the extra disk mass could be abolished by in ice-dominated impactor, allowing some mass to vaporize on impact and escape the system [7]. (2) The moons' compositions, densities, and possible porosities can result by adding ice to the system, as the vaporization of water will also help to protect carbonaceous materials that partly form the moons from being altered during impact, as well as bring water to the Martian system. (3) The water would also be key for forming Deimos beyond the synchronous orbit, as the viscous interaction between dust and vapor would help extend the impact disk [7][8].

Methods: For this study, Smoothed Particle Hydrodynamic (SPH) simulations of giant impacts with impactors of varying ice content were performed to create an impact-generated disk, from which Phobos and Deimos would form [9]. We used the Tillotson Equations of State to model both the iron-rock Mars and the water-ice and basalt impactor [10]. We started with an impactor ~3% the mass of Mars, ~10^5 total SPH particles, impacting at 1.4x escape velocity at an angle of 45 degrees, with compositions of the impactor of 0.0 (for comparison), 0.1, 0.3, 0.5, 0.7, 0.9, and 1.0 fraction of water-ice mantle to basalt core. From the SPH simulation data, we determined each particle type (planet, disk, or escape) based on orbital and energy parameters. Escape particles were those whose velocities were over escape velocity from Mars and disk particles were those whose angular momentum was greater than the angular momentum at Mars' surface and whose semi-major axis was larger than Mars' radius. To reach convergence in the disk mass, this process was iterated until the number of particles tagged as disk particles did not change by more than 0.01%. The final disk masses, temperatures, and compositions were compared to understand the effect of the impactor's water-ice content on the system.

Results & Discussion: We found that, compared to previous studies, the disk mass produced by an impactor with any amount of ice was larger (Figure 1). This effect is due to three possible mechanisms: (1) numerical error due to simulation resolution at the core-mantle boundary; (2) the radius of impactors containing ice is larger, allowing more material to spray out into the disk in the 45° grazing impacts; and (3) the water-ice absorbs some of the impact energy through vaporization, which cools disk temperatures (see Figure 3), lowering particle velocities, and keeping less particles from escaping the system.

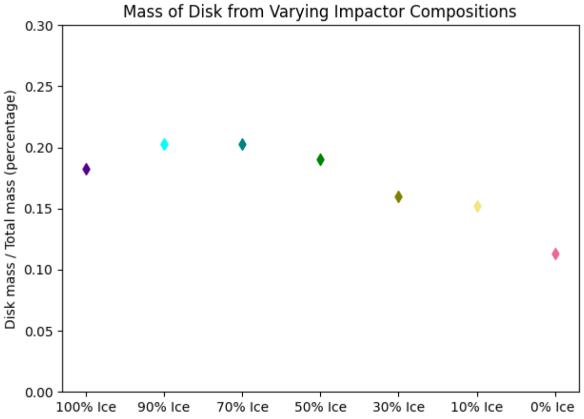

Figure 1: Total disk mass normalized by the total system mass for each initial impactors' water-ice content.

We also found that an impactor of 0.3 and larger ratio of water-ice to basalt formed disks containing more than 50% water, which will be important when forming Deimos as the water vapor-grain interaction can spread the impact disk (Figure 2) [7][8]. The moons also are shown to have a small basaltic composition, which is in line with MGS-TES (Mars Global Surveyor Thermal Emission Spectrometer) data analyzed by [11] that found a portion of Phobos' surface was possibly basalt in composition, a possible similarity to the Martian crust. The large water content of the disk was found to decrease disk temperatures, allowing for temperature changes before and after impact to be less than the melting temperature for silicates (~1200°C) for impactors containing more than 30% ice, and at a low enough temperature to prevent destruction/extreme alteration of chondrites (<500°C) for impactors containing more than 70% ice (Figure 3) [12]. This suggests that chondritic materials, of which the moons are suspected to be composed of, can survive a giant impact event. The existence of water in the impact-generated disk also suggests that water may condense, accounting for the possible water-ice content of the moons.

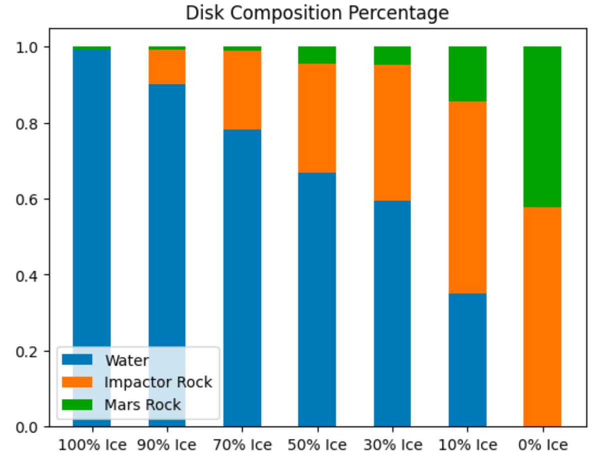

Figure 2: Percentage compositions of the impact-generated disk for different initial impactor compositions, with blue being the water content, orange being the basalt from the impactors' core, and green being basalt from Mars' mantle.

The best case for reproducing the moons' proposed compositions are the 70% and 90% water-ice mantle impactor cases, as they allow for low disk temperatures and more chances for chondritic materials to survive. In our current solar system, an object with around 70% or 90% water-ice content is not exactly realistic, as the object with the highest amount of water content in our current solar system, Ganymede, only is about 50% water. However, recent work concerning samples from the asteroid Ryugu estimate that Ryugu's parent body may have been made up of around 20-90% water from looking at aqueously-formed mineral assemblages present in the sample [13]. Therefore, in the early solar system, during the time this Mars impact may have occurred, an object with around 70% water-ice may have been feasible. This impactor would have come from the outer solar system around the time of giant planet instability, in which outer solar system bodies were flung into the inner solar system, though the timing of the impact needs to be constrained by the formation ages of the Phobos and Deimos [14].

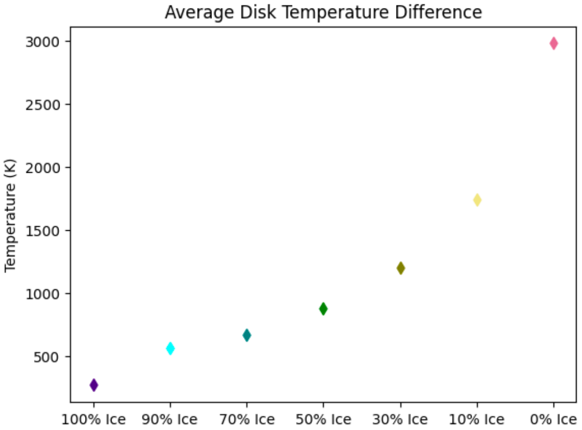

Figure 3: Temperature difference (in K) of the impact-generated disk before and after impact for simulations with different initial impactor compositions.

Future Work: Using more advanced equations of state (MANEOS), we will more accurately model chondritic materials using serpentinite instead of basalt. We will track temperature changes of SPH particles through the whole impact event in order to understand how many chondritic materials survive the impact. We will also look at smaller impactors following the work of Canup and Salmon, 2018, which found that a Ceres/Vesta sized impactor would be sufficient to forms the moons.

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