THE ORIGIN OF CALLISTO'S VALHALLA BASIN: FIRST RESULTS OF SPH IMPACT SIMULATIONS AND THE SEARCH FOR THE IMPACTOR'S ORIGIN. Philip M. Winter[1], Thomas I. Maindl[1], Mattia A. Galiazzo[1], and Christoph M. Schäfer[2], [1]Department of Astrophysics, University of Vienna, Türkenschanzstr. 17, 1180 Vienna, Austria, [2]Institut für Astronomie und Astrophysik, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 10, 72076, Tübingen, Germany

Introduction: We explore the formation of the Valhalla crater on the Jovian moon Callisto focusing on the perspectives of the impact-induced formation process itself and the origin of the impactor. The former is performed via smooth particle hydrodynamics (SPH) imapct simulations, the latter by a genetic n-body algorithm study on possible impactor families.

Among other big basins, Valhalla was first found by the Voyager probes and later studied in more detail by the Galileo mission. The Valhalla crater system measures ~3000 km in diameter, containing a bright central area of ~700 km, a ridge system, as well as a ring system in the outskirts of the crater. As many details of the complex crater formation process itself are still poorly understood we study the projectile's origin and properties as well as the Valhalla crater formation process, and the inner structure of Callisto.

In the context of possible habitable regions in our Solar System, subsurface oceans have moved into the focus of interest. Jupiter's icy moons possibly have such oceans underneath their icy crust. We investigate a possible subsurface ocean on Callisto, Jupiter's outermost big moon ([1], [2]).

While subsurface oceans are typically found by satellite missions and advanced observation techniques ([3], [4]), we study Callisto's interior by reconstructing its biggest crater Valhalla with some hundreds of kilometers in diameter.

Method: Studying collisions between minor and major bodies by n-body simulations is computationally demanding. Typically, one has to constrain the parameter space of the minor bodies to selected regions within the Solar System (e.g. Kuiper belt objects or specific families of objects). We use a genetic algorithm (GA) ([5]) to find families of asteroids and comets that are likely to collide with Callisto or Ganymede. Hereby, we cope with the large parameter space of initial orbital elements (see Table 1). The GA increases the performance by several orders of magnitude compared to classical searching grids and produces a reasonable number of data-points to do a statistical analysis of typical impactor families ([6]). For the n-body integrations, we use Lie-Series as described in [7].

We simulate the crater-forming impact using our own 3D SPH code including elasto-plastic continuum mechanics and a damage model for fracture and brittle failure as introduced in [8] and [9] and successfully used for cratering in the past (e.g., [10], [11]). We use the Tillotson equation of state with parameters from [12] and [13] (liquid water), respectively.

	min	max
a [AU]	4.9501	30.33
e	0	0.99
i [deg]	0	180
ω [deg]	0	360
Ω [deg]	0	360
M [deg]	0	360

Table 1. Parameter space for initial conditions in the vicinity of Jupiter. The symbols denote the classical orbital elements.

Results: Figure 1 gives first results on the distribution of close encounter velocities of test masses with Callisto. The GA is designed to find collisional or close encounter orbits using an iterative set of n-body simulations. Each iteration process results in a data point shown in Figure 1. Based on these first results in addition to results of previous studies (cf. [6]), we chose a "typical" impact velocity of 18.2 km/s and an impact angle of 40° (measured from the vertical so that 0° corresponds to a head-on collision) for the detailed SPH impact simulations.

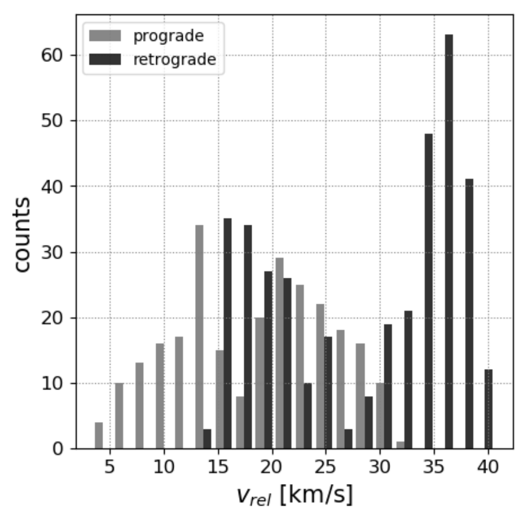

Figure 1. Histogram of close encounter velocities with Callisto resulting from GA-based simulations.

The impact simulations assume two- and three-layered models of Callisto. Both have a 150-km icy crust which – in one model – floats on a 100-km liquid subsurface ocean on the core. The other model does not have a subsurface ocean. Figure 2 shows the profile of the final crater in the model without a subsurface ocean. The color-coded material damage shows that the crust is damaged only in the vicinity of the impact site (the "damage-ring" at the border between the core and the crust is a numerical artefact). Also, the

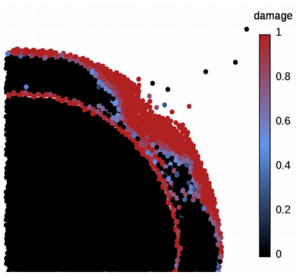

Figure 2. Final crater after an impact at 18.2 km/s and an angle of 40° (head-on is 0°). Model without subsurface ocean, material damage is color coded. See text for details.

crater shape does not resemble the observed mere distorted surface around the impact site ([14]). Introducing the subsurface ocean forms a temporary transient crater with a diameter of approx. 350 km (see Fig. 3, left column) which subsequently completely disappears by interaction with the ocean leaving behind the observed distorted area (Fig. 3, right column). Also, the damage to the icy crust does not stay localized in the vicinity of the impact site. Rather, quickly after the impact the crust gets completely fractured due to radial pressure waves propagating throughout the subsurface ocean (cf. Fig. 3, bottom panel).

Conclusions: We were able to get preliminary results on collisions with Callisto using a novelty GA-approach that allows to cover a much larger parameter space than previous methods. Based on collision velocity and impact angle distributions, we simulate "likely" impacts onto Callisto and are able to roughly reproduce the observed data of the Valhalla basin. We confirmed the necessity of a subsurface ocean for explaining the observed nature of that basin.

In the future, we will study possible origins of the impactor that formed Valhalla more closely ([15]), considering asteroid families like the Centaurs as possible source. Also, we will continue to reefing our material model to more accurately simulate the impact process itself in order to constrain the projectile's mass and material.

Acknowledgements: The authors acknowledge support from the FWF Austrian Science Fund under projects S11603-N16 (PMW, TIM) and P23810-N16 (MAG), respectively.

References: [1] Khurana K. K. et al. (1998) *Nature*, 395:777–780. [2] Kivelson M. G. et al. (1999) *JGR*, 104:4609–4626. [3] Bender K. C. et al. (1997) *LPS XXVIII*, 89. [4] Croft S. K. (1981) *LPS XII*, 187–189. [5] Turing A. M. (1950) *Mind. LIX* (238): 433–460. [6] Winter P. M. et al. (2017) *EPSC2017*, 795. [7] Hanslmeier A. & Dvorak R. (1984) *A&A*, 132, 203 [8] Maindl T. I. et al. (2013) *AN*, 336, 996. [9] Schäfer C. et al. (2016) *A&A*, 590, A19. [10] Maindl T. I. et al. (2015) *A&A*, 574, A22. [11] Haghighipour N. et al. (2016) *ApJ*, 830, 22. [12] Benz W. & Asphaug E. (1999) *Icarus*, 142, 5. [13] Brundage A. L. (2013) *Procedia Engineering*, 58, 461. [14] Bender K. C. (1994) *LPS XXV*, 91. [15] Winter P. M. et al. (2018) *in prep.*

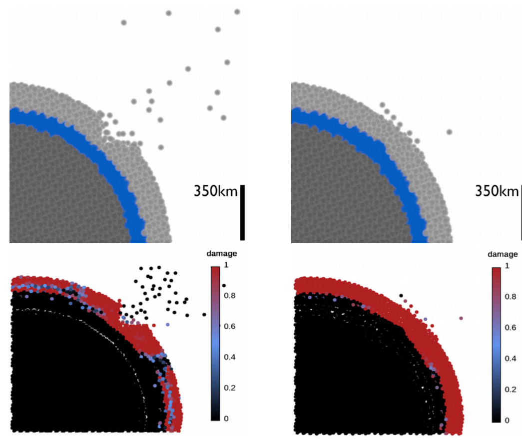

Figure 3. Top panel: crater-forming impact snapshots with subsurface ocean (blue) underneath the icy crust. Bottom panel: the damage plot shows that pressure propagating throughout the ocean damages the entire crust. Left column: transient crater, right column: final crater. The impact velocity and angle are like in Fig. 2.