Uranus Giant Impacts at High Resolution

J. A. Kegerreis[1], V. R. Eke[1], R. J. Massey[1], L. F. Teodoro[2], C. L. Fryer[3], D. G. Korycansky[4], M. S. Warren[5], K. J. Zahnle[6]. [1]Institute for Computational Cosmology, Durham University, Durham, DH1 3LE, UK; [2]BAER/NASA Ames Research Center, Moffett Field, CA, USA; [3]Los Alamos National Laboratory, Los Alamos, NM, USA; [4]CODEP, Department of Earth Sciences, University of California, Santa Cruz, CA 95064, USA; [5]Descartes Labs, 1925 Trinity Drive, Los Alamos, NM, USA; [6]NASA Ames Research Center, Moffett Field, CA, USA; jacob.kegerreis@durham.ac.uk

Introduction: Uranus spins on its side. With an obliquity of 98° and its major moons orbiting in the same tilted plane, the common explanation is that a giant impact sent the young Uranus spinning in this new direction [1]. The impact might also help explain other phenomena, such as the striking differences between Uranus' and Neptune's satellite systems [2, 3], the remarkable lack of heat from Uranus' interior [4, 5, 6], and its highly asymmetrical and off-axis magnetic field [7].

The violent event itself has been studied little since the smoothed particle hydrodynamics (SPH) simulations of Slattery et al. in 1992 (hereafter S92) [8]. We are performing new simulations of the impact with 100 to 1000 times better mass resolution, allowing the detailed modelling of, for example: Uranus' atmosphere and its fate; the post-impact debris disk; and the deposition of the impactor's material and energy inside Uranus; as well as, of course, the testing of S92's original conclusions for the types of impacts that could have produced the present-day spin.

The very first simulations of the Uranus impact were done specifically to investigate whether the shock from the collision would blast away Uranus' hydrogen-helium atmosphere [9]. This has a much lower density than the inner ice and rock material, so requires high resolution (i.e. many SPH particles) to model; hence its necessary absence in S92's $<10^4$-particle simulations [8]. Our initial results with 10^6-10^7 particles suggest that much of the atmosphere can survive a typical 2 $M_\oplus$ impact (see Fig. 1), but much of the parameter space is still being explored.

Uranus' equatorial ring and satellite system is remarkable in several respects. It features a set of regular, prograde, major moons, a compact inner system of rings and small satellites, and a distant group of irregular moons. The inner system and major moons are hypothesised to have formed either from a post-impact debris disk [4, 8] or from a pre-impact proto-satellite disk that was destabilised by the post-impact debris disk and rotated to become equatorial [2, 10]. The more-distant irregular satellites are thought to have been captured after the impact [3]. Unlike Earth's Moon-forming collision, which has been widely studied and simulated, Uranus' satellites are a tiny fraction (10^{-4}) of the total system mass. Whereas this corresponded to just under the mass of a single particle in S92's simulations, we resolve this with thousands of particles, allowing us to investigate the amount, distribution, and composition of material available for satellite formation.

Uranus is extremely cold, with a uniquely low luminosity in approximate equilibrium with solar insolation [11]. This might be explained by restricted interior convection, perhaps caused by the deposition of the impactor's energy into a thin shell [4, 5, 6]; another aspect that high-resolution simulations can start to probe.

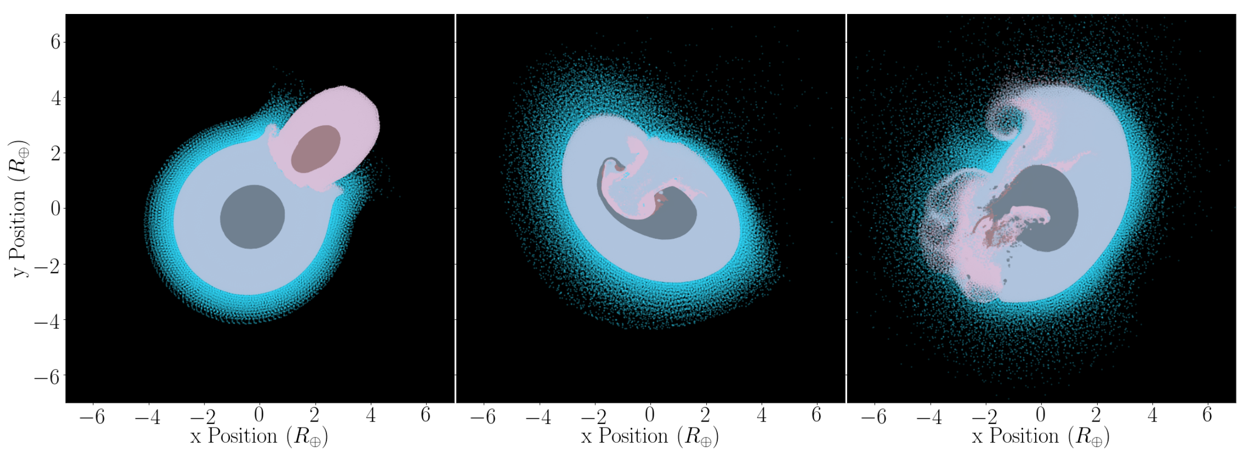

Figure 1: Snapshots from a simulation with 10^6 SPH particles in the pre-impact Uranus and 1.2×10^5 in the impactor (for similar-mass particles), at times of 3000, 6000, and 9000 s after the start of the simulation, with a cut around $z = 0$. The particles are coloured to show their material and ones with larger smoothing lengths are plotted more transparently. For Uranus and the impactor respectively: grey and brown are the rocky cores; light blue and pink are the ice layers; and turquoise is the H_2-He atmosphere.

Simulations: The simulations are being run with a modified version of the parallel tree-code HOT [12]. We are running a suite of 10^6 and 10^7 particle simulations with detailed runs of 10^8 particles also planned.

Planets contain multiple and complex materials, so the equations of state (EoS), which relate the pressure, density, and temperature (or similar), are important components of SPH impact simulations.

We are initially using the EoS defined by Hubbard and MacFarlane (1980) [13], implemented in the code as tables for interpolation, making it easy to switch in and compare the effects of other EoS in the future. Following their Uranus models, we use a differentiated three-layer set-up with a rocky core, icy mantle, and hydrogen-helium atmosphere [13]. The impactor has the same rock and ice layers but no atmosphere. The radial profiles (of density, temperature, and so on) are created by integrating inwards in thin spherical shells from the surface, using the EoS to maintain hydrostatic equilibrium. The radii of the layer boundaries are iterated until the profile satisfies the observational constraints of the total mass and the moment of inertia [5].

Spherical Initial Conditions: We also present a new method of placing particles for SPH simulations, such that every particle has a density within 1% of the desired value (Kegerreis et al., 2018, in prep.). This leads to initial conditions that are quick to produce, close to equilibrium, and in which every particle has a realistic density and, therefore, pressure. This also avoids the need for an extra simulation to first relax the system, which can be computationally expensive for these large numbers of particles, as well as avoiding the various problems with the typical alternative of lattice-based methods [14].

Similar ideas motivated the work of Raskin and Owen (2016) [17] and Reinhardt and Stadel (2017) [18]. One issue with the former's method is that a few particles in every shell have serious overdensities (see Fig. 2), causing unrealistically high pressures with a stiff EoS. In the latter's method, only restricted numbers of particles can be placed in each shell and some particles show SPH densities more than 5% discrepant from the profile.

Our method involves distributing any arbitrary number of particles in spherical shells, a non-trivial problem [15]. We begin by dividing the sphere into equal-area regions, followed by stretching slightly away from the poles. Concentric shells can then be set up to precisely follow an arbitrary radial density profile with very low scatter in each shell, as shown in Fig. 2 with a 10^5 particle example for clarity. The discrepancies at the boundaries are a separate issue, caused by the density estimator itself in the simple form of SPH used for this test [16].

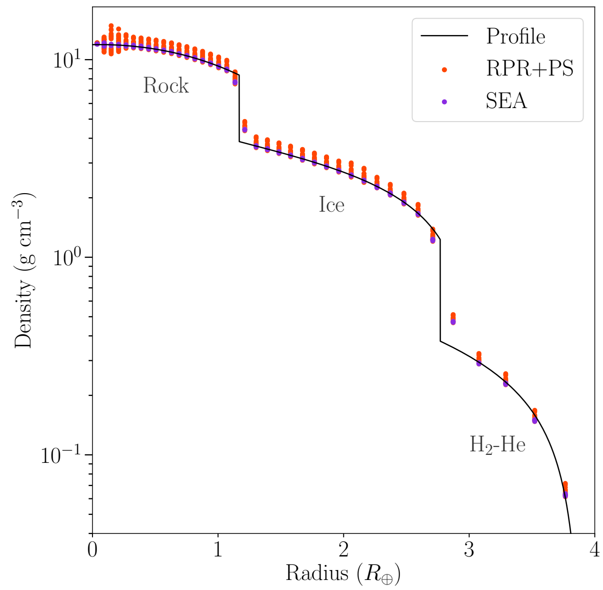

Figure 2: The SPH densities of 10^5 particles placed using our stretched equal-area (SEA) method and the recursive primitive refinement and parametrised spirals (RPR+PS) of Raskin and Owen (2016) [17] for comparison. The black line shows the model density profile of a pre-impact Uranus.

Initial Results: Fig. 1 shows a few snapshots from a test simulation with just over 10^6 particles. Although the system continues to evolve after the third snapshot, we can already see that much of the atmosphere survives the impact; not much material (and very little rock) was scattered into a debris disk; and the impactor material remains fairly localised within Uranus' interior. Other impact scenarios can show quite different behaviour.

References

[1] V. S. Safronov. *Soviet Astron.*, 9:987–991, 1966.
[2] A. Morbidelli, et al. *Icarus*, 219:737–740, 2012.
[3] M. G. Parisi, et al. *Astron. Astrophys.*, 482:657–664, 2008.
[4] D. J. Stevenson. *Lunar and Planetary Science Conference*. 1986.
[5] M. Podolak and R. Helled. *Astrophys. J. Lett.*, 759:L32, 2012.
[6] N. Nettelmann, et al. *Icarus*, 275:107–116, 2016.
[7] N. F. Ness, et al. *Science*, 233:85–89, 1986.
[8] W. L. Slattery, et al. *Icarus*, 99:167–174, 1992.
[9] D. G. Korycansky, et al. *Icarus*, 84:528–541, 1990.
[10] R. M. Canup and W. R. Ward. *Nature*, 441:834–839, 2006.
[11] J. C. Pearl, et al. *Icarus*, 84:12–28, 1990.
[12] M. S. Warren and J. K. Salmon. *Proceedings of the 1993 ACM/IEEE conference on Supercomputing*, pages 12–21, 1993.
[13] W. B. Hubbard and J. J. MacFarlane. *J. Geophys. Res.*, 85:225–234, 1980.
[14] M. Herant. *Mem. Soc. Astron. It.*, 65:1013, 1994.
[15] E. B. Saff and A. B. J. Kuijlaars. *The Math. Int.*, 19:5–11, 1997.
[16] M. M. Woolfson. *Mon. Not. R. Astron. Soc.*, 376:1173–1181, 2007.
[17] C. Raskin and J. M. Owen. *Astrophys. J.*, 820:102, 2016.
[18] C. Reinhardt and J. Stadel. *ArXiv e-prints*, 2017.