Giant Impacts at High Resolution: Uranus, Atmospheric Erosion, and Observability of Exoplanet Collisions

J. A. Kegerreis[1*], V. R. Eke[1], L. F. Teodoro[2], R. J. Massey[1], M. Schaller[3]. [1]Institute for Computational Cosmology, Durham University, Durham, DH1 3LE, UK; [2]BAERI/NASA Ames Research Center, Moffett Field, CA, USA; [3]Leiden Observatory, Niels Bohrweg 2, 2333 CA Leiden, Netherlands. *jacob.kegerreis@durham.ac.uk

Introduction: Giant impacts are thought to dominate many planets' late accretion and evolution. We see the consequences of these violent events on almost every planet in our solar system, from the formation of Earth's Moon to the odd obliquity of Uranus spinning on its side.

Such collisions can also build, erode, or completely destroy a young atmosphere. The recent discovery of many Earth- to Neptune-mass exoplanets and their remarkably diverse range of atmospheres [1] motivates further study of the consequences of giant impacts outside our solar system, in addition to the specific examples closer to home.

For Uranus, as well as the origin of its tilt [2], the giant impact might also help explain other phenomena, such as the striking differences between Uranus' and Neptune's satellite systems [3, 4], the remarkable lack of heat from Uranus' interior [5, 6], and its highly asymmetrical and off-axis magnetic field [7].

Giant impacts are most commonly studied using smoothed particle hydrodynamics (SPH) simulations, where planets are modelled with many particles that are evolved under gravity and material pressure. Much like the size of a telescope, the number of simulation particles limits the objects that can be resolved and studied, such as planets with thin atmospheres or the details of debris. Standard works today use 10^5 up to 10^6 SPH particles. However, using more particles to enable new discoveries is a serious computational challenge and, much like building a bigger telescope, is very (computationally) expensive. For this reason, most studies of atmospheric erosion have instead used analytical approaches and 1D simulations to estimate erosion from a range of head-on impact energies [8], leaving much of this complex field still to be explored.

In addition to opening up new studies that were previously out of reach, the importance of improving resolution for existing topics as well was demonstrated by Hosono et al. [9]. Concerningly, simulations that gave apparently reliable results with up to 10^6 particles had not actually converged when re-tested with 10^7 and 10^8.

Here, we present results from simulations with over 10^8 SPH particles to study giant impacts in unprecedented detail. This jump of 100–1000 times better resolution allows much more detailed study of the evolution of Uranus and its atmosphere following a giant impact. We also consider the observability of similar collisions that are expected to occur between exoplanets around other stars.

Methods: We ran a suite of simulated giant impacts on the young Uranus with a wide range of impact angles and masses [10], and have repeated a couple of specific cases with 10^5, 10^6, 10^7, and 10^8 simulation particles for more detailed study. We use a simple Uranus model with Hubbard & MacFarlane's equations of state [11] for a rocky core, mixed-ice mantle, and hydrogen-helium atmosphere.

SWIFT (SPH With Inter-dependent Fine-grained Tasking) is a next-generation hydrodynamics and gravity code for astrophysics and cosmology in open development (swift.dur.ac.uk), designed from the ground up to run fast and scale well on modern supercomputing architectures [12].

For the past decade, physical limitations have kept the speed of individual processor cores constrained, so instead of getting *faster*, supercomputers are getting *more parallel*. This makes it ever more important to share the work evenly between every part of the computer so that no cores are sitting idle and wasting time.

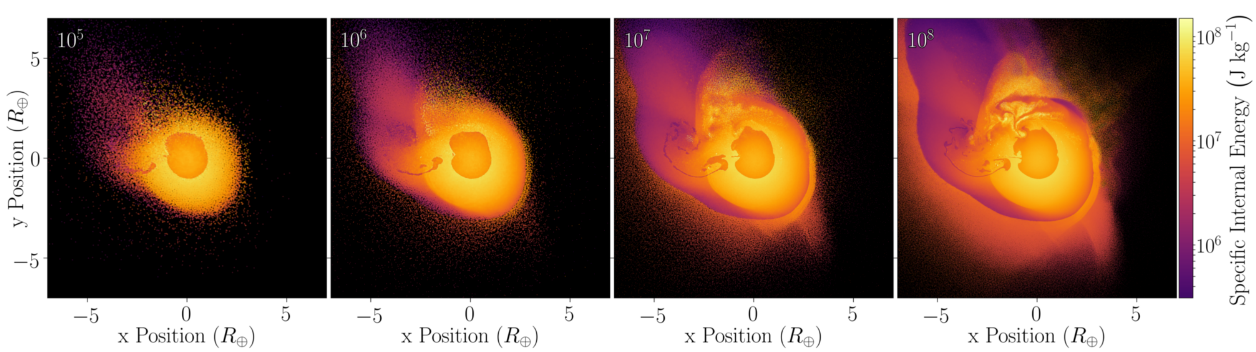

Figure 1: Mid-collision snapshots of the same giant impact on Uranus at the same time from simulations with the $\sim 10^5$ SPH particles (left panel) typical in the literature, up through 10^6 and 10^7 to the 10^8 (right panel) made possible with SWIFT, resolving some of the detailed evolution of both internal structure and debris. An animation of the highest resolution impact in motion is available at icc.dur.ac.uk/giant_impacts.

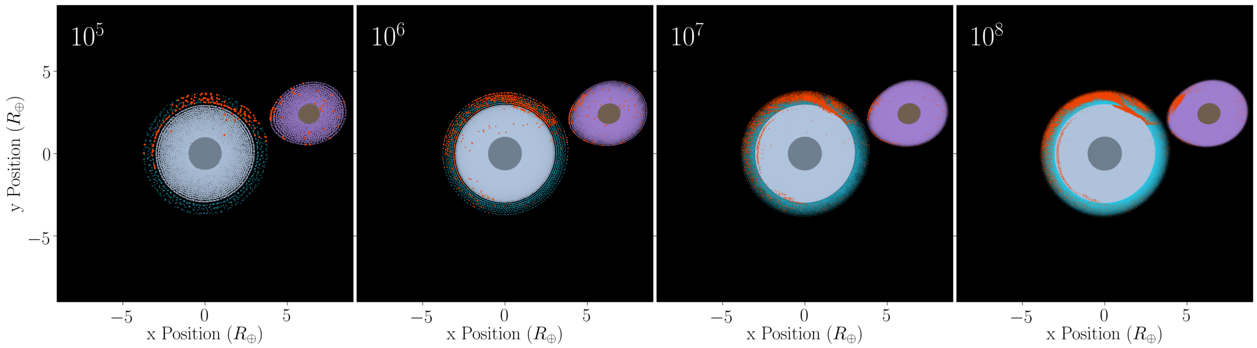

Figure 2: The particles that will become unbound and escape the system, highlighted in orange on a pre-impact snapshot from the same simulations with $\sim 10^5$–10^8 SPH particles as in Fig. 1. Only particles in a thin cross-section are shown for clarity. Light and dark grey show the target's ice and rock material, respectively, and purple and brown show the same for the impactor. Light blue is the target's H-He atmosphere. The total mass lost is similar in all cases, but 10^5–10^6 particles fail to resolve the detailed results.

SWIFT's speed is partly a result of its task-based approach to parallelism and domain decomposition, making sure we divide up the *work* instead of just the *data*.

Results: We confirm the findings from the single previous study of lower resolution ($<10^4$ particles) simulations [13] that an impactor with a mass of at least 2 $M_\oplus$ can produce sufficiently rapid rotation in the post-impact Uranus, for a wide range of angular momenta.

For more-grazing impacts, most of the impactor's ice and energy can be deposited in a hot, high-entropy shell at a radius of ~ 3 $R_\oplus$. This might help explain Uranus' observed lack of heat flow from the interior and be relevant for understanding its asymmetric magnetic field [6]. In all cases, at least 90% of the atmosphere remains bound to the final planet after the collision, but over half can be ejected beyond the Roche radius.

Fig. 1 shows a comparison of a typical impact simulated at different resolutions. Although the overall behaviour is encouragingly similar, and large-scale results like the rotation rate are consistent, other details like the tidal stretching of the impactor's core and the distribution of the debris cannot be fully resolved by the 10^5 or 10^6 particle simulations.

For example, Fig. 2 highlights the particles that the impact will eject from the system. The total atmospheric erosion is consistent in all cases, but the higher resolutions reveal new details. The initial collision blasts away much of the outer atmosphere and some ice, some of which will escape but most remains gravitationally bound. The 10^7 and 10^8 particle runs show that the deeper shell of now-exposed particles then gets ejected during the subsequent violent oscillations as the impactor remnants fall back in and the planet starts to settle.

The composition of the atmosphere is of interest both for constraining the details of collisions like this on Uranus and for understanding the chemistry and spectra of exoplanet atmospheres, many of which may have also been disrupted by similar impacts. Fig. 3 shows that trace amounts of the impactor's rocky core become mixed into the outer envelope, but that 10^5–10^6 particles are far too few to model this type of process.

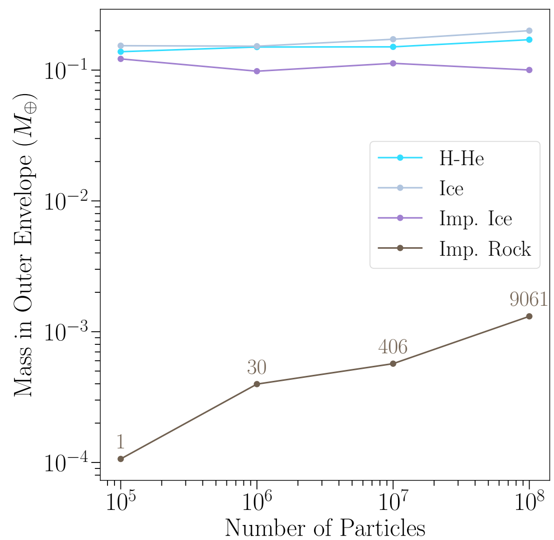

Figure 3: The mass of target and impactor materials that get mixed into Uranus' outer atmosphere after the impact, for the different resolution simulations. The annotations show the corresponding number of SPH particles.

We are now using these results to estimate the observability from the collisional heating and scattered debris of such a giant impact if it occurred around another star. Combined with observed exoplanet populations and more detailed simulations of atmospheric erosion, these can help constrain models of planet formation.

References

[1] E. D. Lopez & J. J. Fortney. *Astrophys. J.*, 792:1, 2014.
[2] V. S. Safronov. *Soviet Astron.*, 9:987–991, 1966.
[3] A. Morbidelli, et al. *Icarus*, 219:737–740, 2012.
[4] M. G. Parisi, et al. *Astron. Astrophys.*, 482:657–664, 2008.
[5] M. Podolak & 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] N. K. Inamdar & H. E. Schlichting. *Astrophys. J.*, 817:L13, 2016.
[9] N. Hosono, et al. *Publ. Astron. Soc. Jpn.*, 69:26, 2017.
[10] J. A. Kegerreis, et al. *Astrophys. J.*, 861:52, 2018.
[11] W. B. Hubbard & J. J. MacFarlane. *J. Geo. Res.*, 85:225, 1980.
[12] M. Schaller, et al. *Proc. of PASC'16*, ACM, 2:1–10, 2016.
[13] W. L. Slattery, et al. *Icarus*, 99:167–174, 1992.