

**A NEW SUITE OF HYDRODYNAMICAL SIMULATIONS OF THE ORIGIN OF THE OBLIQUITY OF URANUS** Luís F.A. Teodoro<sup>1</sup>, Donald G. Korycansky<sup>2</sup>, Michael S. Warren<sup>2</sup>, Christopher L. Fryer<sup>2</sup>, Gabriel Rockefeller<sup>2</sup>, Kevin Zahnle<sup>3</sup> and Vincent R. Eke<sup>4</sup> <sup>1</sup>BAER, NASA Ames Research Center, Moffett Field, CA 94935-1000 USA (luis.f.teodoro@nasa.gov), <sup>2</sup>CODEP, Dept. of Earth Sciences, University of California, Santa Cruz, CA 95064, USA, <sup>3</sup>Los Alamos National Laboratory, Los Alamos, NM 87585, USA, <sup>5</sup>NASA Ames Research Center, Moffett Field, CA 94935-1000 USA, <sup>4</sup>Institute for Numerical Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK,

High obliquity (98°) is a remarkable feature of the Uranus system. This includes the planet itself and the major satellites that orbit in the planet's equatorial plane. The current paradigm for the cause of this property is that the planet experienced a giant off-axis impact by a large body (of the order of one Earth mass) some time after its formation. Since the seminal work of Slattery *et al* (1992) [1] two decades ago there has not been a major effort to study this problem. We are currently carrying out a new set of simulations using the same method (Smooth Particle Hydrodynamics) as Slattery *et al* [1] but with one hundred to a thousand times better mass resolution ( $10^6$ - $10^7$  SPH particles).

We are employing the parallel tree-code developed by Warren and Salmon (1992) [2] with SPH capabilities enhanced by Warren and Fryer for astrophysical applications and extensively used in cosmological simulations and hydrodynamics (e.g. Warren *et al.*, 2006, 2013; Fryer *et al.*, 2006 [3, 4, 5]).

Here, we report on the findings obtained from our initial suite of 35 SPH simulations of the impact origin of the obliquity of Uranus.

**Initial conditions** The initial conditions are generated using the algorithm introduced by Diehl *et al* [6] and further improved by Teodoro *et al* [7]. Briefly, the target and impactor are generated according to density and temperature profiles that are sampled by a set of SPH particles in a regular grid. To verify whether such a configuration is in hydrostatic equilibrium we compute the forces at the particle location using the SPH code and we move the SPH particles according to the net hydrodynamical force at the particle location. We repeat this procedure until hydrostatic equilibrium is reached. Typically one hundred steps are required to reach con-

vergence.

The rock/iron core is assumed to be isothermal. The velocity of the impactor is set at 5 km/h at infinity. The temperature at 1 bar is such that it agrees with the current observed effective temperature (78 K at  $P = 1$  bar).

Our suite of simulations explores a range of parameter space and tests the conclusions of the work by Slattery *et al.* Furthermore, it takes advantage of the vastly higher mass (and spacial) resolution to place additional constraints on the process, by means of investigating possible post-impact satellite formation. Additionally, we are currently testing various combinations of proto-Uranus structures and compositions with the aim of constraining the impact given our present-day knowledge about the interior of the planet.

**Equations of State** (EOSes) are important components of hydrodynamic simulation programs. This is especially true for calculations that include multiple materials, as these do. Based on our knowledge of planetary bodies, we require the ability to represent iron, silicate material (e.g. dunite), ices (principally H<sub>2</sub>O ice), and hydrogen-helium mixtures. We focused on incorporating advanced formulations, such as ANEOS, or SESAME from the Los Alamos National Laboratory, which are too complex to be efficiently evaluated analytically during a calculation, and are thus represented in tabular form which can be used as look-up tables for interpolation during a simulation. Components such as iron or silicate material (“rock”, represented by dunite) are presently incorporated in tabular form (SESAME iron, ANEOS dunite). SESAME is provided by T-1 Group at Los Alamos National Laboratory (<http://aphysics2.lanl.gov/opacity/opacdocs/sesame.html>), and

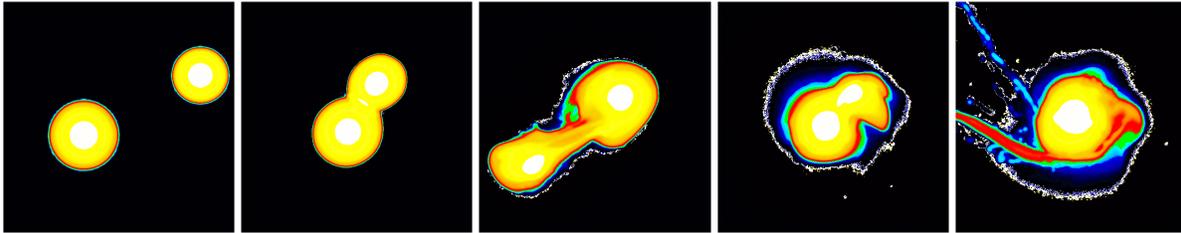


Figure 1: Snapshot images rendered from our planetary collision simulation. Colors represent the logarithm of projected density. White and blue denote the high- and low-density regions, respectively. The images are chronologically ordered from the left to the right. The initial impact comes into the system from the upper-right, making initial contact with the proto-Uranus with a relative velocity of 5 km/h. In the center, the “impactor” and initial debris approaches for a secondary collision. In the bottom row, the cores of the proto-planets have merged, leaving an orbiting stream of iron-poor material. This simulation used over 1 SPH million particles with the equations of state detailed in the text. The images show the events up to  $\sim 20$  hrs after the impact. The different snap-shots represent the time-steps 200, 1200, 4000, 10000 and 17000.

ANEOS is described by Thompson and Lauson (1984). We have successfully implemented routines to read the EOS tables and interpolate from them into the hydrodynamics code and are able to make use of SESAME and ANEOS tables. However, we have found that our initial formulation of the interpolation routines adds a significant amount of computational time to the calculation, compared to a simple analytic EOS, such as a perfect gas or analytic formulae such as those presented by Hubbard and Macfarlane (1980) for outer-planet structure models. We are also at the present time using an analytic representation for ices in Hubbard and MacFarlane (1980).

## References

- [1] W. L. Slattery, W. Benz, and A. G. W. Cameron. Giant impacts on a primitive Uranus. *Icarus*, 99:167–174, September 1992. doi: 10.1016/0019-1035(92)90180-F.
- [2] J. Salmon and M. Warren. Skeletons from the Threecode Closet. *J. Comp. Phy.*, 111:136–155, March 1994.
- [3] M. S. Warren, K. Abazajian, D. E. Holz, and L. Teodoro. Precision Determination of the Mass Function of Dark Matter Halos. *ApJ*, 646: 881–885, August 2006. doi: 10.1086/504962.
- [4] M. S. Warren. 2HOT: an improved parallel hashed Oct-Tree N-Body algorithm for cosmological simulation. In *SC 13: Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis*, pages (LA–UR–13–22336), 2013.
- [5] C. L. Fryer and M. S. Warren. The Collapse of Rotating Massive Stars in Three Dimensions. *ApJ*, 601:391–404, January 2004. doi: 10.1086/380193.
- [6] S. Diehl, G. Rockefeller, C. L. Fryer, D. Riethmiller, and T. S. Statler. Generating Optimal Initial Conditions for Smooth Particle Hydrodynamics Simulations. *ArXiv e-prints*, November 2012.
- [7] L. F. A Teodoro, V. R. Eke, D. G Korycansky, M. S. Warren, C. L. Fryer, G. Rockefeller, K. Zahnle, and V. R. Eke. A New Initial Conditions Generator for planetary sciences. *In Preparation, to be submitted to ApJ*, January 2015.