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How Uranus Fell Over: Giant Impact Simulations at High Resolution

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Why Does Uranus Spin on its Side?

The common explanation for Uranus' unique obliquity of 98° is that a proto-planet at least as large as the Earth crashed into the young planet, sending it spinning in this new direction[1].

We run high-resolution smoothed particle hydrodynamics simulations of the collision with 10^5-10^8 particles using the HOT and new SWIFT codes[2,3]. With these, we study which kinds of impacts could have caused the tilt and whether this cataclysmic event might also explain other features like Uranus' oddly low temperature, strange magnetic field, and unusual satellite system.

Both ~head-on (Fig. 1) and more grazing (Fig. 2) types of impact can reproduce the spin, but have different effects on the internal structure[4].

[1] Safronov (1966). *Sov. Astron.*, 0:987-991.
[2] Warren & Salmon (1993). *ACM/IEEE SC*, 12-21.
[3] Schaller et al. (2016). *PASC16*, 2.
[4] Kegerreis et al. (2018). *ApJ*, 861:52.
[5] Slattery et al. (1992). *Icarus*, 99:167-174.
[6] Pearl et al. (1990). *Icarus*, 84:12-28.
[7] Nettelmann et al. (2016), *Icarus*, 275:107-116.

Animations — Click me!

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Which Impacts Produce Enough Spin?

Increasing the angular momentum changes how fast the impact makes Uranus spin. At first, for a set impactor mass and velocity, the higher the angular momentum the faster the final spin and the shorter the rotation period. However, the impactor soon starts to only graze the target and eventually misses the proto-Uranus completely, unable to transfer over its huge angular momentum. A wide range of 2 and 3 Earth-mass impacts generate more than enough spin. The planet could then slow down by interacting with satellites and the debris disk, but impacts are the only way to spin faster. These results broadly agree with the original low-resolution simulations of Slattery et al. (1992)[5] with 10^4 particles.

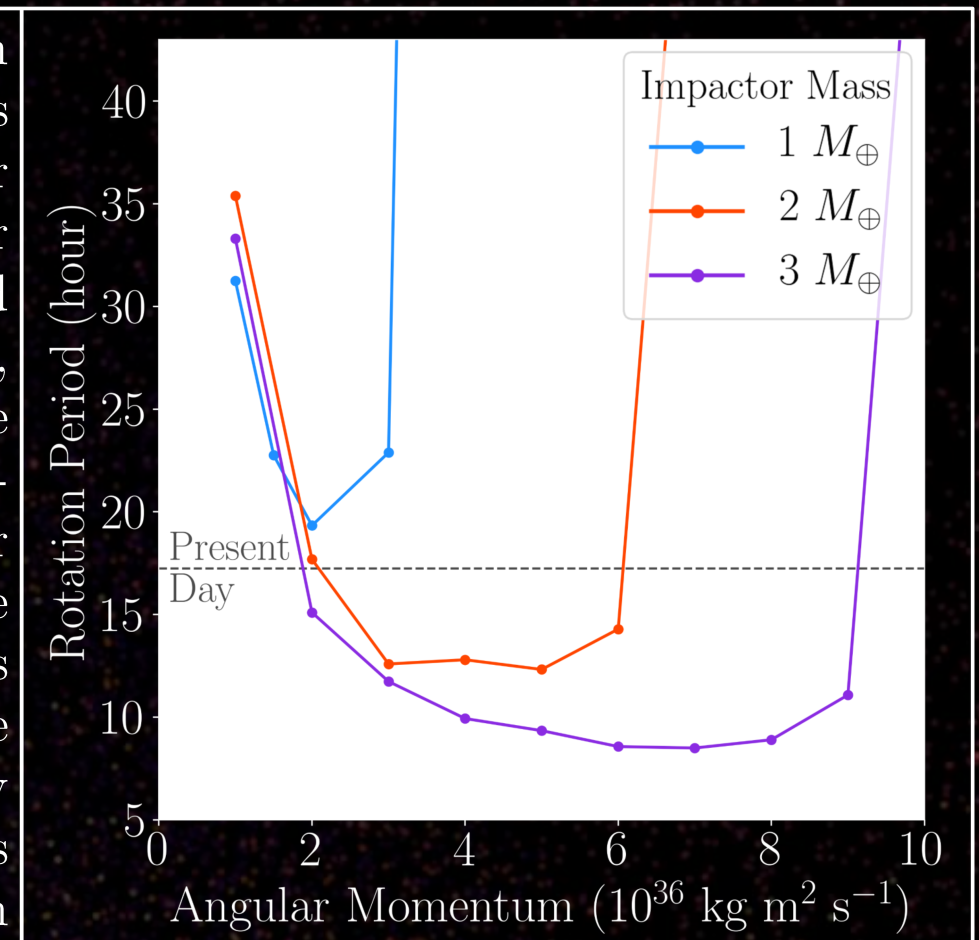

Figure 3: The rotation periods of the post-collision planets for different impactor masses and angular momenta.

Can the Impactor Trap the Interior Heat?

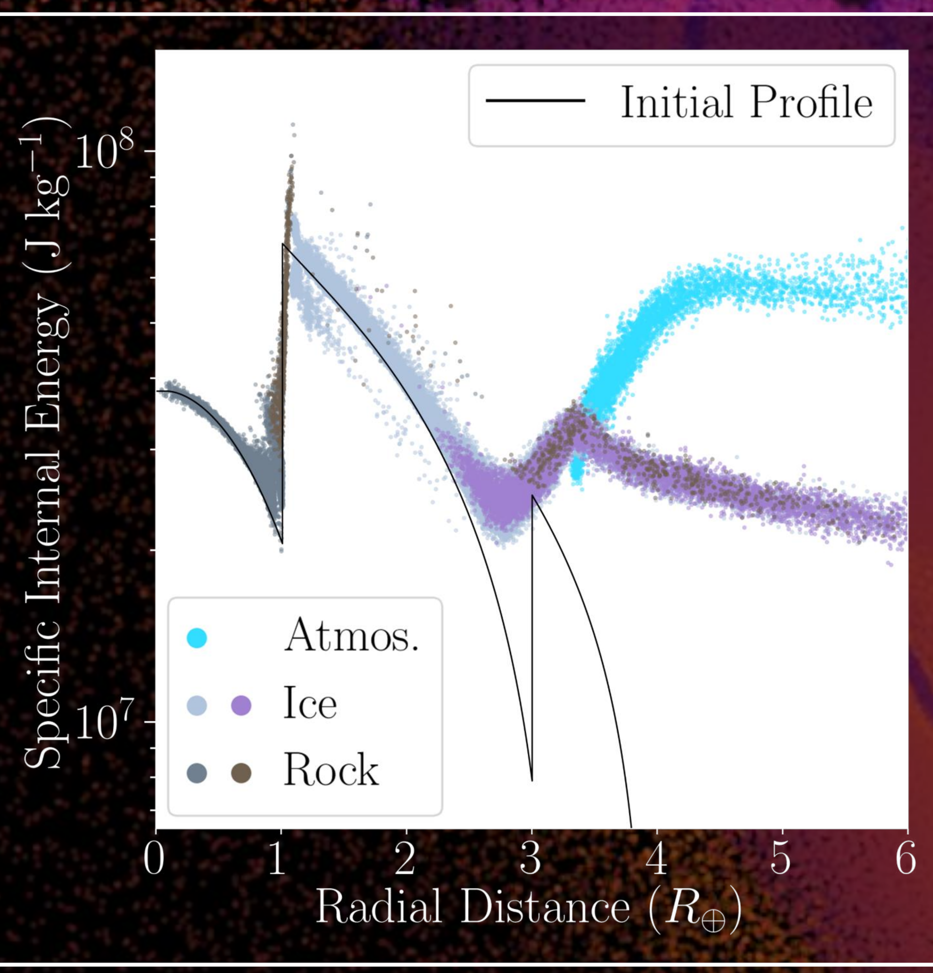

Figure 4: The internal energies of the post-impact particles as a function of radius, compared with the initial ~adiabatic profile.

The exterior of Uranus is extremely cold. In fact, to instrument precision, no heat appears to flow from the interior to the surface[6]. This is strikingly unlike the other giant planets, all of which are thought to have formed with hot interiors and still be slowly radiating out their heat today. One explanation is that, although there are higher temperatures in the interior, the heat is trapped underneath a thermal boundary layer and cannot escape[7]. Our simulations show that the impactor typically deposits its material and energy in a fairly thin shell near the top of the proto-Uranus' ice. This creates a hot, high-entropy layer that can inhibit convection, possibly preventing inner heat from reaching the surface today.

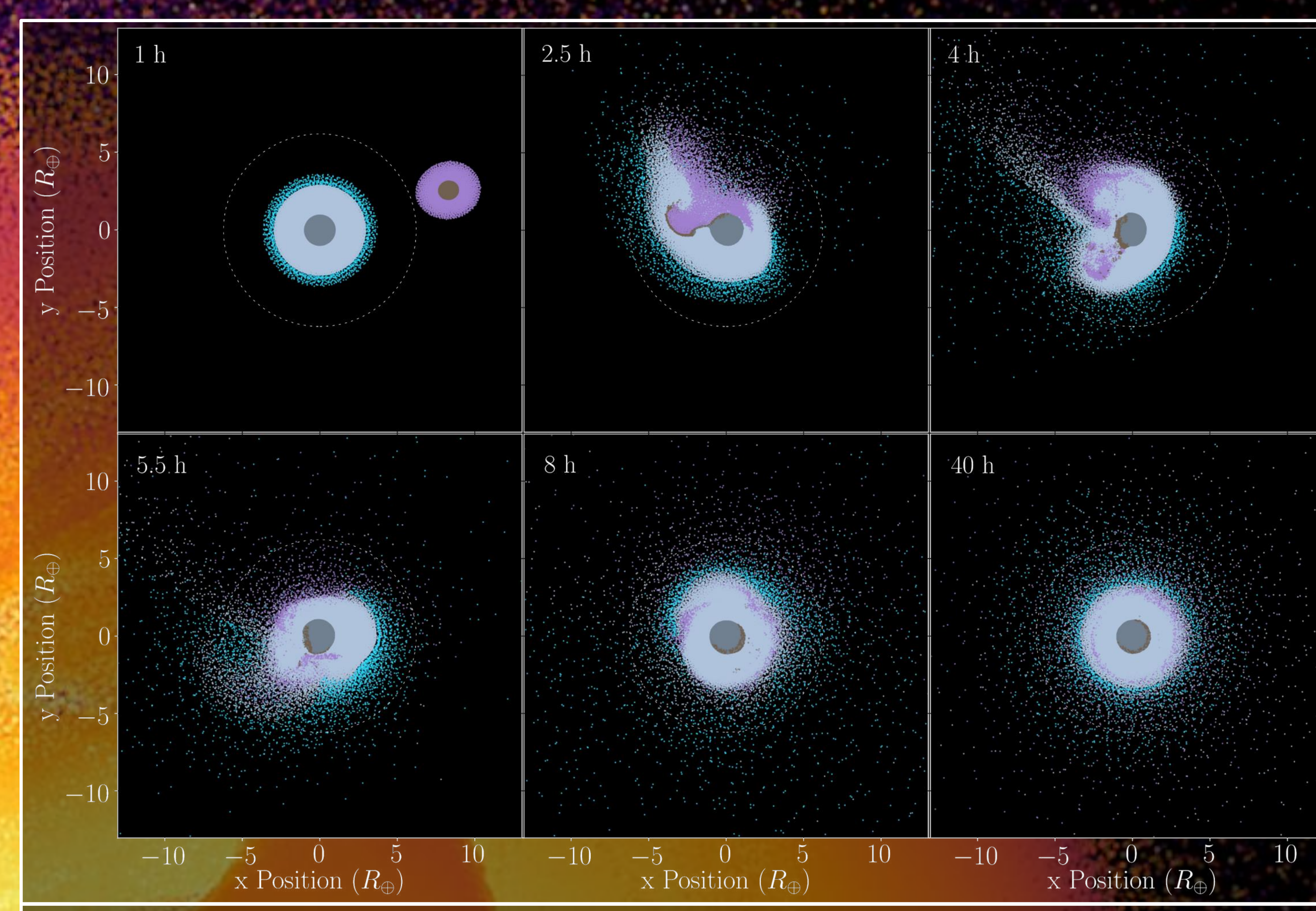

Figure 1: Snapshots from a typical low angular momentum impact.

Background image: A mid-collision snapshot from a 10^7 particle simulation, coloured by the internal energy. The impactor's core is being stretched out into a long stream, some of which remains in stable orbits where it might collapse to form satellites.

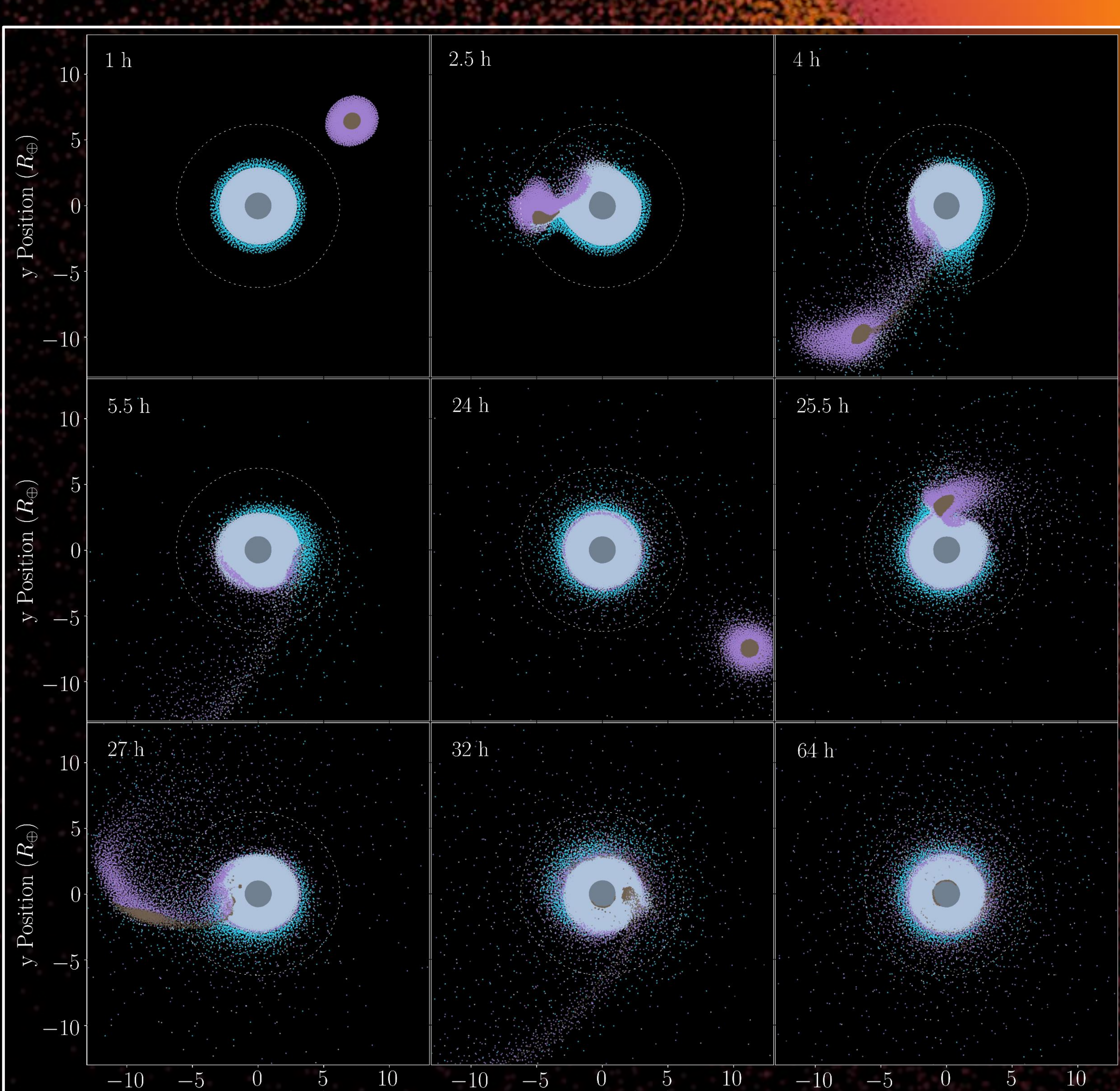

Figure 2: Snapshots from a typical high angular momentum impact.

How much Atmosphere Survives the Impact?

As violent as the impacts appear, most of the hydrogen-helium atmosphere remains bound to the system, since the expected speeds are less than the escape velocity. However, depending on the angular momentum, only a little atmosphere might remain inside the Roche radius and fall back to become part of the post-impact planet.

The tiny density of the atmosphere compared with the ice and rock layers means that many particles (i.e. high resolution) are required to model it accurately. As such, these are the first 3D simulations to model atmosphere loss from oblique giant impacts, so there are many more details in this area for us to explore.

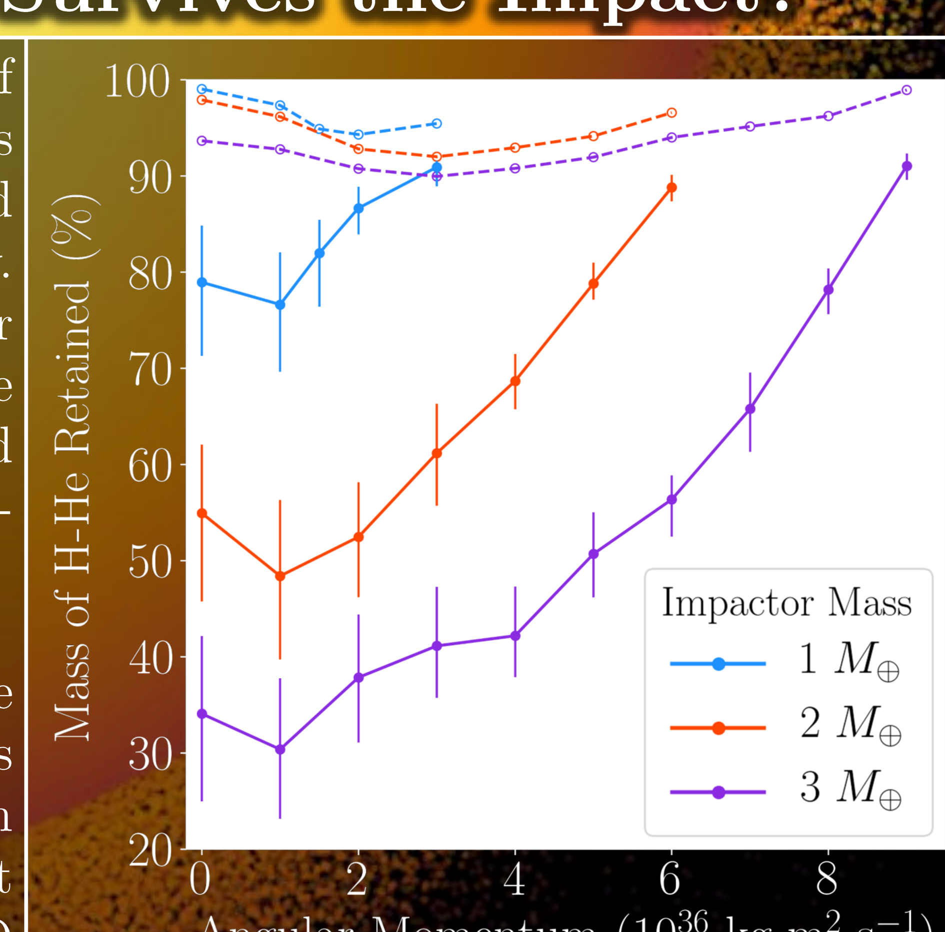

Figure 5: The proportion of the atmosphere retained inside the Roche radius (6 ± 0.5 $R_\oplus$; solid) and bound to the system (dashed).