HOW THE SOLAR SYSTEM SURVIVED A VIOLENT EPOCH OF DYNAMICAL INSTABILITY

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EXECUTIVE SUMMARY

The solar system's outer planets (Jupiter, Saturn, Uranus, and Neptune) formed in just a few million years, while gas was still present in the Sun's primordial protoplanetary disk [1]. Although the evolution of these outer planets is well studied [2,3], the leading models seem to be incompatible with the solar system's terrestrial system (Mercury, Venus, Earth, and Mars) [4]. By performing thousands of N-body simulations of an orbital instability in the outer solar system occurring in conjunction with terrestrial planet formation, we presented the first complete evolutionary model for the solar system that explains both its inner and outer regimes. Additionally, we conducted the largest-ever suite of planet-formation simulations using a realistic model that accounts for the effects of fragmentation as bodies collide [5]. Finally, we used a GPU-accelerated code [6] to accurately model dynamics down to realistic mass resolutions during the solar system's earliest epoch, and in the young asteroid belt.

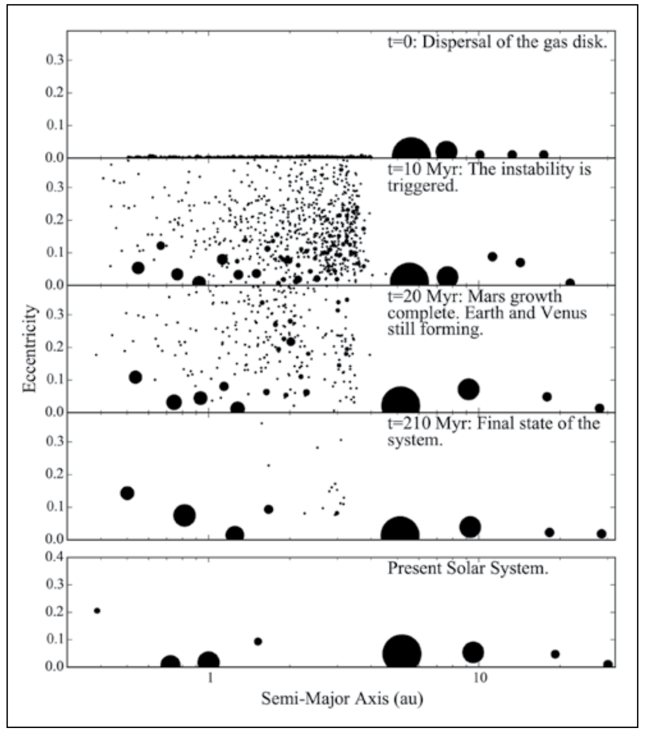

Figure 1: Semi-Major Axis vs. orbital eccentricity plot depicting the evolution of a successful system. The size of each point corresponds to the mass of the particle; because Jupiter and Saturn are hundreds of times more massive than the terrestrial planets, we use separate mass scales for the inner and outer planets.

RESEARCH CHALLENGE

Accurately modeling the late stages of planet accretion is subject to numerical limitations and simplifications. In particular, to keep the calculation tractable, most authors [7,8] employ integration schemes that neglect collisional fragmentation. The initial planet-forming disk, which in reality contained millions of solid objects with a range of masses, must be approximated with just over a thousand bodies (the majority of which are assumed not to interact gravitationally with one another). Nevertheless, such studies have proved successful at replicating the general orbits of the inner planets. However, explaining Mars' small mass (just 10% that of the Earth) and rapid formation (about ten times faster than the Earth, as inferred from isotopic dating [9]) requires substantial modification to the standard theory of planet formation [8,10]. Furthermore, the asteroid belt's low total mass (only a few percent that of the moon) and unique dynamical structure are still largely unexplained [7,8,10]. Earth and Mars are both in the Sun's "potentially habitable" zone, yet Mars is small, barren, and unable to support a robust atmosphere. Understanding the dynamical mechanisms that prevented Mars from growing into an Earth-like planet will give us insight into how special our own world really is.

METHODS & CODES

For our fragmentation simulations, we use a modified version of the Mercury6 hybrid integrator, written in Fortran [11,13]. Our simulations of terrestrial accretion begin with the simplest initial conditions and are consistent with observations of proto-stellar disks [1,7,8]. To systematically test the effects of a giant planet instability, we perform several batches of integrations and trigger the instability during different epochs of terrestrial growth. To investigate the effect on the asteroid belt, we use a GPU code written in CUDA C (GENGA, [6]) to reperform successful integrations with a larger number of objects in the belt region. Because gas-disk interactions are complex, the exact mass and planetesimal size distribution profiles that emerge from the primordial gas (and go on to form the inner planets) are not well known. Therefore, our "simple" initial conditions might not be representative of physical reality. We investigate this problem as well, using GPU acceleration. We employ a forcing function to mimic the effects of gas drag and utilize a multiannulus approach to track the accretion of millions of small objects in the infant terrestrial disk.

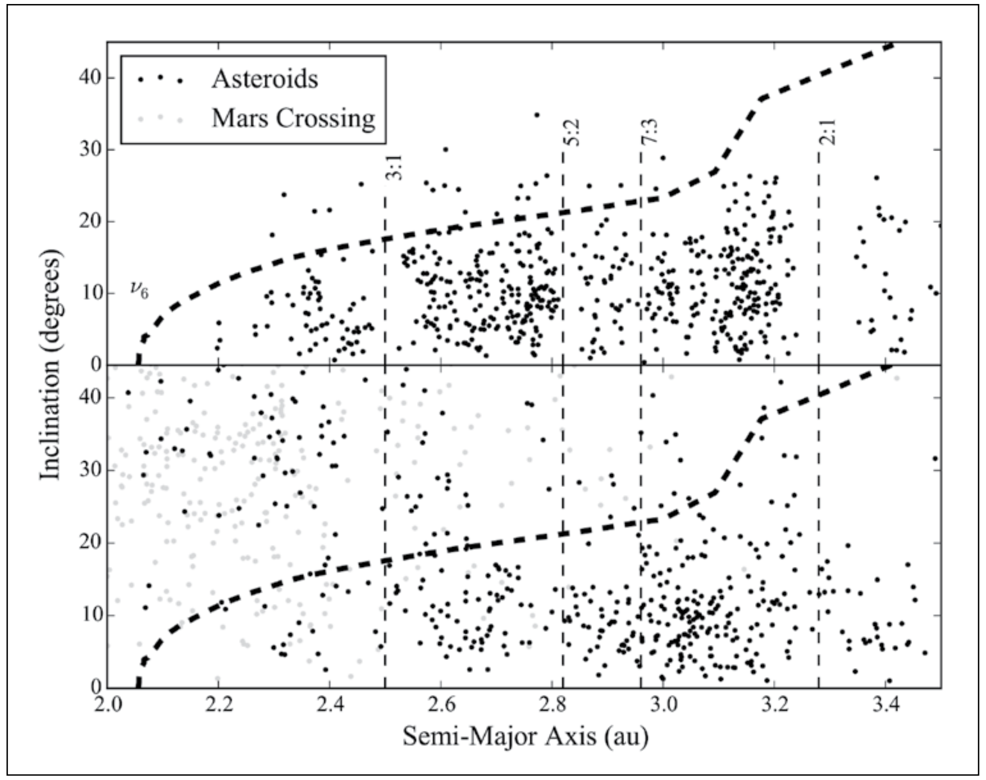

Figure 2: Semi-Major Axis vs. orbital inclination plot comparing the actual asteroid belt (top) with our simulated asteroids (bottom). The dashed lines denote important orbital resonances. Grey points correspond to asteroids on Mars-crossing orbits, which will be removed naturally during subsequent evolution.

RESULTS & IMPACT

Our work offers a simple and elegant explanation for Mars' small size and rapid growth. Our instability simulations consistently outperform our control runs when measured against a variety of success criteria. These include the orbits, masses, and geological formation timescales of the planets; the size and orbital structure of the asteroid belt; and the water content of Earth. When the instability occurs approximately 1–10 million years after gas disk dispersal, "Mars" is just one of several Mars-sized objects with similar orbits (Fig. 1). The frequent perturbations from the increasingly eccentric orbits of Jupiter and Saturn quickly cause these objects (and similar bodies in the asteroid belt) to either be ejected from the system or scatter inward towards the proto-Earth (sometimes to deliver water). In successful simulations, Mars undergoes no further accretion events after the instability, while Earth and Venus continue to grow (thus matching their relative geological formation times [9]). Additionally, we find that accounting for collisional fragmentation results in fully grown systems of terrestrial planets that are better matches to the actual solar system in terms of their orbital excitation (eccentricities and inclinations) and planet spacing (particularly that of Earth and Venus). Furthermore, the instability proves successful at reproducing the broad orbital distribution of large objects in the asteroid belt (Fig. 2). Thus, an early dynamical instability among the giant planets can simultaneously explain the structure of both the inner and outer solar system.

WHY BLUE WATERS

Blue Waters' unique capabilities and highly supportive staff were crucial to the success of this project. Our study relied heavily on the use of GPU accelerators on Blue Waters' XK nodes. Having the ability to efficiently run large suites of GPU-accelerated jobs led us to seek out a Blue Waters allocation. Furthermore, our initial work on Blue Waters has spurred several follow-on projects and greatly accelerated my progress in graduate school.

PUBLICATIONS & DATA SETS

Clement, M., et al., Mars' growth stunted by an early giant planet instability. *Icarus*, 311 (2018), DOI:10.1016/j.icarus.2018.04.008.

Matthew Clement is a third-year PhD candidate in astrophysics at the University of Oklahoma. He is working under the supervision of Nathan Kaib and expects to receive his doctorate in August 2019.