THE EARLY INSTABILITY SCENARIO FOR PLANET FORMATION IN THE SOLAR SYSTEM

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EXECUTIVE SUMMARY

The solar system's outer planets (Jupiter, Saturn, Uranus, and Neptune) formed rapidly, while gas was still present in the infant solar system [1]. While the outer planets' evolutionary history is rather well understood by theorists [2,3], the leading models seem to be incompatible with the solar system's terrestrial system (Mercury, Venus, Earth, and Mars) [4]. The research team has used large suites of N-body simulations of the solar system's earliest epochs of formation and growth to develop a new, robust model for the solar system that explains both its inner and outer regimes. Additionally, the team conducted the largest-ever suite of planet formation simulations using a realistic code that accounts for the effects of fragmentation as bodies collide [5]. The team also used GPU acceleration [6] to accurately model dynamics down to realistic mass resolutions during the solar system's earliest epoch, and in the young asteroid belt. Finally, the team performed a detailed investigation into the origin of the solar system's most peculiar planet, Mercury.

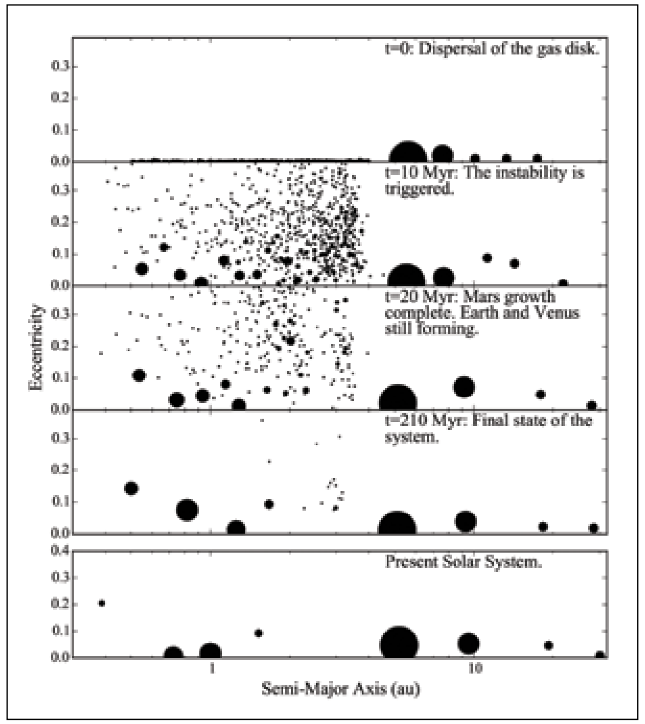

Figure 1: Semi-major axis vs. orbital eccentricity plot depicting the evolution of a successful system. The size of each point corresponds to the mass of the particle. (Because Jupiter and Saturn are hundreds of times more massive than the terrestrial planets, the team used separate mass scales for the 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 Earth) and rapid formation (about 10 times faster than 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 the fragmentation simulations, the team used a modified version of the Mercury6 hybrid integrator, written in FORTRAN [11,13]. The simulations of terrestrial accretion begin with the simplest initial conditions, consistent with observations of proto-stellar disks [1,7,8]. To systematically test the effects of a giant planet instability, the team performed several batches of integrations and triggered the instability during different epochs of terrestrial growth. To investigate the effect on the asteroid belt, the researchers used 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, "simple" initial conditions might not be representative of physical reality. The team investigated this problem using GPU acceleration as well. Further, they employed a forcing function to mimic the effects of gas drag, and utilized a multi-annulus approach to track the accretion of millions of small objects in the infant terrestrial disk.

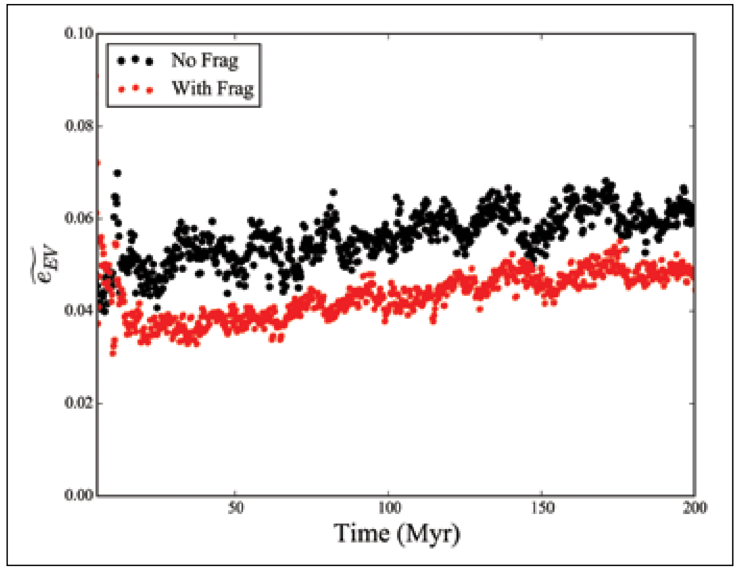

Figure 2: Eccentricity evolution of Earth and Venus analogs with (red) and without (black) collisional fragmentation. Since the total particle number stays higher for longer when fragmentation is included, the orbits of the growing analogs are damped more strongly by dynamical friction.

RESULTS & IMPACT

This work offers a simple and elegant explanation for Mars' small size and rapid growth (Fig. 1). The instability simulations consistently outperform the control runs when measured against a variety of success criteria. 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, the team found 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; Fig. 2) and planet spacing (particularly that of Earth and Venus). Furthermore, the instability proves successful at depleting a primordially massive asteroid belt (consistent with disk models [8]) at the 99.9% level. Thus, an early dynamical instability among the giant planets can simultaneously explain the structure of both the inner and outer solar system.

Of further note, recent work performed on Blue Waters has uncovered a potential solution to another long-standing problem in planetary science. All previous evolutionary models of the solar system generate populations of highly inclined asteroids inconsistent with the observed solar system. This work has found that these asteroids are naturally removed during Saturn's phase of orbital migration. It also found a fossilized record of this phase of depletion in the distribution of asteroidal precession rates.

WHY BLUE WATERS

Blue Waters boasts state-of-the-art resources that were invaluable to the success of this project. The research relied on GPU accelerators on XK nodes almost exclusively. Having the ability to efficiently run large suites of GPU-accelerated jobs led the PI to seek out a Blue Waters allocation.

PUBLICATIONS & DATA SETS

M. Clement *et al.*, "Excitation and depletion of the asteroid belt in the early instability scenario," *Astron. J.*, vol. 157, 2019, doi: 10.3847/1538-3881/aaf21e.

M. Clement *et al.*, "The early instability scenario: Terrestrial planet formation during the giant planet instability and the effect of collisional fragmentation," *Icarus*, vol. 321, 2019, doi: 10.1016/j.icarus.2018.12.033.

M. Clement *et al.*, "Dynamical constraints on Mercury's collisional origin," *Astron. J.*, vol. 157, 2019, doi: 110.3847/1538-3881/ab164f.

Matthew Clement received a Ph.D. in astrophysics in May 2019 from the University of Oklahoma, There, he worked under the direction of Nathan A. Kaib.