Giant planets migrated shortly after the Solar System's protoplanetary disk dispersed

Early in the history of the Solar System, the giant planets – including Jupiter and Saturn – migrated under gravity into different orbits around the Sun, causing an epoch of chaos and collisions. Radioactive isotopes in asteroids record the thermal imprint of these collisions, and a broad survey of meteorites now constrains the timing of the migration to approximately 11 million years after the Solar System formed.

The question

When did giant planets migrate? The answer to this question helps to answer the even more important question: how did the giant planets migrate? These answers matter because planetary migration seems to be a quotidian feature among planetary systems, including our own. This process not only shapes the final architecture of a planetary system, but it mixes protoplanetary reservoirs, seeding terrestrial planets with water and carbon-rich materials from the outer Solar System and perhaps playing a role in setting the stage for the origins of life[1]. The 'when' and 'how' of giant-planet migration provide a framework for understanding the evolutionary pathways of planetary systems like our own. However, with several possible time-dependent stimuli for planet migration (Fig. 1a) and ongoing debate around the timing of the Solar System's episode of giant-planet migration, both 'when' and 'how' remain open questions.

The solution

To constrain the timing of giant-planet migration in the Solar System, we looked to asteroidal meteorites. The parent bodies of these meteorites formed in the first few million years of Solar System history, and they would have been part of any episode of planetary collisions in the dynamical chaos ensuing giant-planet migration. Thermochronologic mineral systems in meteorites record the timescales of heating and cooling in these parent bodies through the temperature-sensitive retention of radiogenic isotopes. We compiled a database of thermochronologic ^{40}K–^{40}Ar system ages from chondritic meteorites to search for the thermal imprint of the energetic collisions associated with giant-planet migration. We developed an asteroid-scale thermochronologic model that simulates both endogenic and impact heating and coupled this to a Markov-chain Monte Carlo algorithm to invert the thermochronologic ages of our database and recover the timescales of intense bombardment concomitant with giant-planet migration.

The results of our inversion support two key conclusions. First, chondritic meteorites (deriving from approximately six distinct parent bodies) collectively record evidence for a single episode of intense bombardment in early Solar System history, a signal consistent with an episode of giant-planet migration. The second conclusion regards the timing of migration. Figure 1b shows the posterior distribution of bombardment (or migration) onset times, constrained by our model and database of ^{40}K–^{40}Ar ages. The histogram overlies the characteristic timescales of various mechanisms of giant-planet migration, including gas-giant migration embedded in a gaseous protoplanetary disk[2] and dynamic instabilities triggered by gas dispersion[3], self-unstable systems[4], or interactions with a massive outer planetesimal disk[4]. Approximately 75% of the posterior distribution post-dates the gas disk's lifespan, including its median (11.3 My_{ss}, where My_{ss} indicates millions of years after Solar System formation) and mean (15.0 My_{ss}). We have concluded that giant planets likely migrated via a dynamic instability resulting from the unstable orbital arrangements left behind after the dispersal of the gaseous protoplanetary disk.

The implications

Our results provide an estimate for the timing of giant-planet migration and its causal mechanism in the Solar System's history. This may help guide the efforts of planetary scientists developing models of Solar System dynamical evolution as well as astronomers observing the evolution of young exoplanetary systems. Based on our results, we suggest that solar-mass stars less than 20 My old are the most promising targets to observe systems undergoing or recovering from giant-planet migration.

A major strength of our study is the large compilation of meteorite thermochronology that integrates the histories of several asteroidal bodies and reflects a broad inner Solar System signal. On the other hand, a recent study on a single chondrite group and its associated asteroid family estimates a timing of giant-planet migration that is approximately 50 My later[5]. Different approaches to the same question of when the giant planets migrated are yielding different results, so we still have work to do as a community to converge.

Every model benefits from incorporating more nuance of the natural systems they simulate. Our future work on this question will implement more detailed thermochronologic models to improve our estimates of asteroid bombardment timescales. We also hope that our findings will inspire cosmochemists and geochronologists to measure more chondrite ^{40}K–^{40}Ar ages with cutting edge analytical and interpretive techniques, to expand the thermochronologic age database that our inversion code relies on. The more high-quality thermochronologic ages, the better!

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EXPERT OPINION

“There is much speculation regarding the onset of giant-planet migration in the Solar System. This work presents the community with an important step forwards in understanding the early evolution of our Solar System. By combining a meteorite-age database with Markov-chain Monte Carlo inversion techniques, the authors conclude that the giant planets radically changed their positions in the first 11 million years of the Solar System’s history.” **Ramon Brasser, Konkoly Observatory, Budapest, Hungary.**

FIGURE

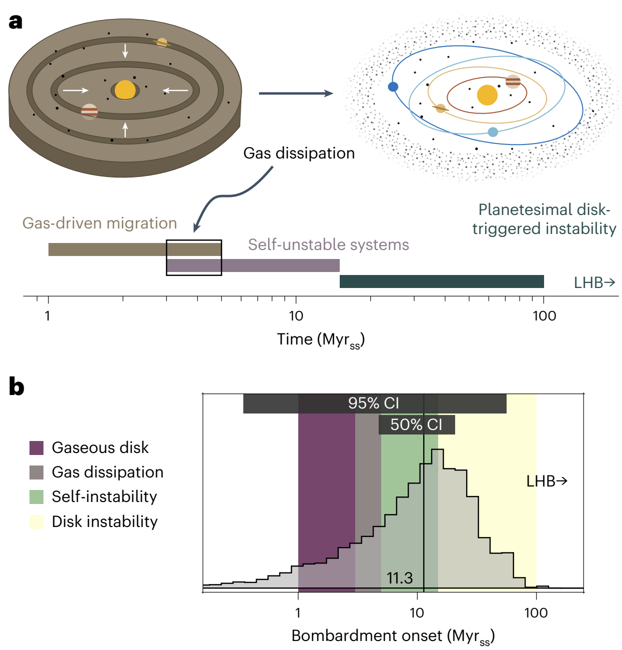

Fig. 1 | The timing of giant-planet migration in the Solar System. **a**, Relevant timescales are shown, in millions of years after Solar System formation (My$_{ss}$), for potential stimuli of giant-planet migration – from inward migration in the gaseous protoplanetary disk, through gas dissipation, to the instability of giant-planet orbits, either through inherited instability or interactions with an outer planetesimal disk. The hypothetical late heavy bombardment (LHB) timescale is much later, at > 400 My$_{ss}$. **b**, The posterior distribution ($n = 10^6$ Markov-chain steps) of bombardment onset dates, from an inversion of chondrite ^{40}K–^{40}Ar thermochronologic ages, is shown against the timescales of the different stimuli. The black line indicates the median date of 11.3 My$_{ss}$. CI, credible interval.

BEHIND THE PAPER

This project emerged from a confluence of our multiple scientific perspectives. We conceived this project through our respective expertise: Elisabeth R. Newton’s in exoplanetary astronomy, C. Brenhin Keller’s in computational geochemistry, and my own in planetary science and cosmochemistry. This study was one of the original ideas proposed (and funded) in my NSF postdoctoral fellowship at Dartmouth College and was a throughline of my postdoctoral work. Cameron W. Stewart joined the project a little later as a student researcher and brought an enthusiasm and excitement for thermochronology and data science that really carried us through our database compilation.

This work was a highly interdisciplinary project that pushed us to branch out far beyond our usual research fields. We all learned so much from each other as well as from the bounty of information contained in meteorite thermochronology. **G.H.E.**

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   This paper reports a timeframe of approximately 60 My after Solar System formation for giant-planet migration, based on dynamical models and chondrite thermochronology.

FROM THE EDITOR

“We roughly know ‘what’ happened during the early stages of Solar System history, but the ‘when’ is still hard to pinpoint. This paper’s answer to that question is notable because it is based on a large dataset of observational data from meteorites, providing a constraint that does not depend strictly on dynamical models as most of the studies on this topic do.” **Luca Maltagliati, Senior Editor, *Nature Astronomy.***