Early terrestrial planet formation by torque-driven convergent migration of planetary embryos

M. Brož[1], O. Chrenko[1], D. Nesvorný[2], N. Dauphas[3]

[1] *Institute of Astronomy, Charles University, V Holešovičkách 2, 18000 Prague 8, Czech Republic*

[2] *Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302, USA*

[3] *Origins Laboratory, Department of the Geophysical Sciences and Enrico Fermi Institute, The University of Chicago, 5734 South Ellis Av., Chicago, IL 60637, USA*

Massive cores of the giant planets are thought to have formed in a gas disk by accretion of pebble-size particles whose accretional cross-section is enhanced by aerodynamic gas drag[1,2]. A commonly held view is that the terrestrial planet system formed later (30–200 Myr after the dispersal of the gas disk) by giant collisions of tens of lunar- to **Mars-size protoplanets[3,4]. Here we propose, instead, that the terrestrial planets** of the Solar System **formed earlier by gas-driven convergent migration of protoplanets toward** $\sim 1\,\mathrm{au}$**. To investigate situations in which convergent migration occurs** and determine the thermal structure of the gas and pebble disks in the terrestrial planet zone, **we developed a radiation-hydrodynamic model with realistic opacities[5,6]. We find that protoplanets** grow in the first 10 Myr **by mutual collisions and pebble accretion, and gain orbital eccentricities by gravitational scattering and the hot-trail effect[7,8]. The orbital structure of the** inner Solar System **is well reproduced in our simulations, including its tight mass concentration at 0.7–1 au and the small sizes of Mercury and Mars. The early-stage protosolar disk temperature exceeds 1500 K inside 0.4 au implying**

that Mercury grew in a highly reducing environment, next to the evaporation lines of iron and silicates, influencing Mercury's bulk composition[9]. On contrary, a dissipating gas disk is cold, and pebbles drifting from larger heliocentric distances would deliver volatile elements.

Computer simulations of late-stage accretion are required to match various constraints[10]. **Here we focus on** the similar semimajor axes of Venus and Earth (only $\simeq 0.3\,\mathrm{au}$ radial separation). **Perhaps** the planetesimal disk was truncated at $\sim 1\,\mathrm{au}$ by Jupiter's inward and then outward migration[11,12]. The cause behind the suggested inner edge at $0.7\,\mathrm{au}$ is less clear, but it might be induced by an 'inverted' gas surface density profile $\Sigma(r)$ which would initially concentrate planetesimals by gas drag[13], or removal of planetesimals by outward-migrating giant planet core[14]. Since a narrow annulus of planetesimals tends to spread over time, however, it is still difficult for those models to reproduce the tight terrestrial planet mass concentration at 0.7–1 au[15]. Measurements of isotopic anomalies also indicate that the terrestrial planets may have formed faster than in the standard model, possibly while the gas disk was still around[16]. **We constructed a radiation-hydrodynamic model of terrestrial protoplanets embedded in gas and pebble disks, because it may have regulated their early growth[17,18] as well as their migration[19].** In our model, hereafter named *Thorin*[7], protoplanets migrate due to several gravitational torque terms (Lindblad, corotation and heating[20]). Protoplanets can grow in mutual collisions and by accreting pebbles but not gas. The simulations included Mercury- to Mars-size protoplanets (0.05 to $0.1\,M_{\mathrm{E}}$, where $M_{\mathrm{E}} = 6 \times 10^{24}$ kg is the Earth mass), initially located in an annulus 0.4–1.8 au (Figure 1). Our fiducial gas disk model[21] is defined by the radial gas flux $\dot{M}$ and kinematic viscosity $\nu(r)$, which is a function of radius r. In particular, $\dot{M} = 10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$, $\nu(r) = 1.1 \times 10^{14}\,\mathrm{cm}^2\,\mathrm{s}^{-1}\,(r/1\,\mathrm{au})^s$, where the exponent smoothly changes with r, from $s_1 = -2$ to $s_2 = +0.5$. The resulting gas surface density $\Sigma(r)$ is radially increasing across the inner portion of the terrestrial zone, $r \lesssim 1\,\mathrm{au}$, and decreasing further out. Such a $\Sigma(r)$ inversion is motivated by studies disks with magneto-rotational instability (MRI)[22], active layers[21], or disk winds[13]. Here we focus on viscous disks and local scales ($\sim 1\,\mathrm{au}$), although on a global scale transport could be inviscid (as discussed by ref. [23]). The gas temperature T and disk aspect ratio $h = H/r$ are controlled by the opacity $\kappa(\rho, T)$[5], where ρ is the gas density. The pebble disk is defined by the pebble flux $\dot{M}_{\mathrm{p}}$ at the outer boundary. All these components affect migration of protoplanets. See Methods and **Supplementary Information (Section A)** for a complete model description.

The simulations were used to compute the migration speed and direction of protoplanets as a function of their mass m and semimajor axis a (Figure 2)[24]. We found that protoplanets with $a > 1\,\mathrm{au}$ migrate inward and protoplanets with $a < 1\,\mathrm{au}$ migrate outward. The absolute value of the torque generally scales as $\Gamma_0 = (q/h)^2 \Sigma r^4 \Omega^2$, where $q = m/M_{\mathrm{S}}$ is the planet-to-Sun mass ratio and Ω the Keplerian angular velocity, but its precise value and sign depend on details how gas flows in the vicinity of each protoplanet. The Lindblad torque is induced by resonant density waves which form two spiral arms. It is usually negative and leads to the inward migration, but it may reduce and *reverse* if the eccentricity is excited to $e > 2h$, e.g., during close encounters between protoplanets. A semi-analytical expression of [24] reveals its dependence on the slopes α, β of Σ, T profiles, $\Gamma_{\mathrm{L}} = \Gamma_0/\gamma_{\mathrm{eff}}\,(-2.5 - 1.7\beta + 0.1\alpha)(0.4h/b_{\mathrm{sm}})^{0.71}$; $b_{\mathrm{sm}} = r_{\mathrm{sm}}/(hr)$, where r_{sm} denotes the smoothing length and γ_{eff} the effective adiabatic index. The corotation torque is related to gas moving along horseshoe-like orbits. It becomes positive for certain slopes of Σ, T. If it is kept unsaturated, e.g., by non-zero viscosity, the corresponding expression[24] is $\Gamma_{\mathrm{c}} = \Gamma_0/\gamma_{\mathrm{eff}}[(1.5 - \alpha - 2\xi/\gamma_{\mathrm{eff}})(0.4h/b_{\mathrm{sm}})^{1.26} + 2.2\xi(0.4h/b_{\mathrm{sm}})^{0.71}]$, where $\xi \equiv \beta - (\gamma - 1)\alpha$ is the slope of entropy $\mathcal{S}(r)$.

The heating torque[20] arises when the gas flow is heated by an accreting protoplanet, which creates an underdense region behind it and thus a positive torque contribution. Taken together, these torques form a convergence zone in our fiducial disk model. The convergent migration must lead to the accumulation of planets near the convergent radius $r_{\rm c} \simeq 1\,{\rm au}$. In fact, $r_{\rm c}$ was likely moving in the course of time, but hereinafter we assume it ended up at $1\,{\rm au}$. The characteristic migration rates computed numerically by our RHD model are ${\rm d}a/{\rm d}t \simeq \pm 10^{-7}$ to $10^{-6}\,{\rm au\,yr^{-1}}$. The protoplanets are therefore expected to move near $r_{\rm c}$ well within the lifetime of the protosolar disk (3–10 Myr). This holds for a range of viscosity parameters, namely for $\nu \simeq 0.3$ to 3 times the nominal value, $s_1 \simeq -3$ to -1, and $s_2 \gtrsim 0$. Based on this result we suggest that the convergent migration of protoplanets is the main reason behind the concentration of the terrestrial planet mass at 0.7–1 au. Planet migration in different disk models (e.g. the Minimum Mass Solar Nebula; MMSN) is discussed in **Supplementary Figure 5**.

We performed long-term accretional simulations with a symplectic N-body integrator called *SyMBA*[25] to examine the effect of convergent migration during the gas disk lifetime on the growth of planets. The radial migration of protoplanets, including the evolution of eccentricity and inclination[7,8,19], was informed from our hydrocode simulations described above and mimicked by additional acceleration terms in *SyMBA* (Methods). Specifically, the migration rate ${\rm d}a/{\rm d}t$ was set as a function of planet mass and orbit (from Figure 2 and similar results that we obtained for other disk models; **Supplementary Section G**). We found that convergent migration leads to rapid accretion of planets with properties that often match the real terrestrial planet system (Figure 3). The results vary, however, due to the stochastic nature of accretion and we thus performed dozens of simulations to statistically characterize them. We set the initial angles (Ω, ω, M) randomly to obtain a random geometry of subsequent close encounters. We found that: (i) 3 to 6 terrestrial planets typically form in $<10\,\mathrm{Myr}$, (ii) planet mass is concentrated at $\simeq 0.7$–1 au, (iii) low-mass, Mercury-to-Mars planets end up on moderately excited orbits at <0.7 au or >1 au, and (iv) collisions between similar-sized protoplanets are relatively common (see also [26]). The system architecture is established by collisions, differential migration and eccentricity damping[19], and is quite sensitive to the timing of the gas disk dispersal. The relative importance of pebble accretion for planet growth depends on the time-integrated pebble flux. For example, for a constant pebble flux $\dot{M}_{\mathrm{p}} = 2 \times 10^{-6}\, M_{\mathrm{E}}\, \mathrm{yr}^{-1}$, the growth is roughly equally contributed by pebbles and protoplanet mergers. Significantly larger pebble fluxes sustained over millions of years would lead to planet overgrowth (i.e., super Earths formation; see ref. [27]) and would weaken radial mass concentration. A more systematic sampling of model parameters could help to 'reverse engineer' the disk conditions and lifetime.

At the heart of our argument, the convergent migration of protoplanets produced just the right conditions, with a strong mass concentration near 0.7–1 au, for the formation of the terrestrial planets[11]. This new model offers a notable advantage over the previously suggested mechanisms of annulus truncation[12], because: (i) convergent migration confines the annulus from *both* sides, and (ii) Venus and Earth are kept within the convergence zone, avoiding problems with their repulsion and weakening of the radial mass concentration[15].

A gas disk nearing the end of its lifespan is expected to be rarefied by viscous spreading/photoevaporation, and consequently cold[28]. To study the orbital behavior of the terrestrial planets just before dispersal of the gas, we evaluated the effect of setting the surface density to values 10 or 100 times lower than the nominal value, $\Sigma_0 = 750\,\mathrm{g\,cm^{-2}}$ at 1 au. For this set of simulations we used power-law profiles $\Sigma(r)$, with the slope similar as in the MMSN. The terrestrial planets were assumed to be nearly formed and close to their present orbital radii. A pebble accretion flux up to $\dot{M}_{\rm p} \simeq 2 \times 10^{-4}\, M_{\rm E}\,{\rm yr}^{-1}$ (corresponding to the heating power $L \simeq 10^{20}\,{\rm W}$) was adopted in *Thorin*. In fact, the flux may have been non-stationary, if pebbles are isolated at pressure bumps, accumulated and eventually released (e.g., when $\Sigma_{\rm p} \gtrsim \Sigma$). Additional heating can be provided by planetesimals, mergers, internal differentiation, and radioactivity. Significantly, we found that the planetary orbits became excited by the hot-trail effect[7,8], which arises due to pebble accretion on protoplanets, release of their kinetic energy, and radiative heating of neighbour gas (see Figure 4). It is especially effective for $\sim$10 times lower Σ, when the thermal capacity of gas is lower but its gravity still substantial. As a result, the orbital eccentricities of planets evolve toward asymptotic values $\simeq$0.015–0.02 and migrating planets avoid capture in orbital resonances. The hot-trail effect can explain the current orbital eccentricities of Venus and Earth (proper $e = 0.02$ and 0.01, respectively), which was never suggested before. Additional changes may have been inflicted in the terrestrial planet system by gravitational perturbations during migration/instability of the giant planets[29,30], although it often leads to over-excitation.

A strict version of this work's main thesis –the terrestrial planets formed early– would imply that the Moon-forming impact occurred early as well ($t_{\rm Moon} < 10\,{\rm Myr}$). Lunar Magma Ocean (LMO) solidification may have occurred much later, because the LMO may have been sustained by tidal heating for hundreds of million years[31]. However, for $t_{\rm Moon} < 10\,{\rm Myr}$, geochemical modeling of the Hf/W system (ref. [32,33] and **Supplementary Section H**) shows that the tungsten anomaly in the mantle of Earth would be generally higher than the observed value, $\varepsilon_{182{\rm W}} = 1.9 \pm 0.1$. We therefore prefer our simulations with *SyMBA* that ended with five (or more) terrestrial protoplanets, thus leaving space for a late Moon-forming impact and $\varepsilon_{182\mathrm{W}}$ decrease through equilibration. A late impact could have spontaneously occurred in a dynamically unstable terrestrial system or been triggered by outer planet migration/instability[34].

The early formation of the terrestrial planets in a gas disk has several important implications. For example, the innermost part of a viscously heated disk can reach the evaporation threshold, T_{ev}, of many minerals. As solids evaporate at the critical radius r_{ev}, they cannot contribute to planet's growth below that radius. This could help to explain the small mass of Mercury. Temperatures in a massive, early-stage protosolar disk shown in Figure 4 reach $T \simeq 1500\,\mathrm{K}$ and create a highly reducing environment in which pebbles drift from larger radii[18] down to $r_{\mathrm{ev}} \sim 0.4\,\mathrm{au}$. Evaporation of pebbles alters the local chemical composition of the gas. This is very different from previous nebular hypotheses which dealt only with a narrow ring of local material. Together with nebular metal-silicate fractionation, it could naturally explain the large Fe core of Mercury[9] and relax constraints on the hypothesized impact-related removal of the silicate mantle[35]. Alternately, in the impact hypothesis, Mercury cannot re-accrete dispersed silicates, which could be more easily achieved if the stripping of Mercury's mantle occurred before dissipation of nebular gas[36]. As the temperature decreases in a low-mass, late-stage disk (Figure 4), moderately volatile elements (e.g., Na, S, K, Cl) could have been delivered by pebbles to Mercury's surface, as needed to explain its non-negligible volatile budget[36].

Towards the end of the disk's lifetime, the gas density and viscous heating decrease, but the disk midplane is still shadowed, thus allowing the snowline to move down to $\sim 1\,\mathrm{au}$[28,37]. This could create the right conditions for water delivery to the Earth if the flux of icy/hydrated pebbles from $> 3\,\mathrm{au}$ remained sufficiently high for sufficiently long time. **Given the D/H ratio of the ocean water** (1.5×10^{-4})**, the best match among existing reservoirs are carbonanceous chondrites. However, the importance of this process would diminish if Jupiter and Saturn totally block the flux of icy pebbles from** $> 5\,\mathrm{au}$**[38], and an alternative delivery by planetesimals is more likely[39]. For comparison,** we calculate that the Earth would accrete 1–1.5% of pebbles moving past 1 au. To deliver 1 Earth ocean worth of water $(2.3 \times 10^{-4}\,M_{\mathrm{E}})$, we would need that $f\dot{M}_{\mathrm{p}}\delta t \sim 0.02\,M_{\mathrm{E}}$, where $0 < f < 1$ is the mass fraction of water in pebbles, $\dot{M}_{\mathrm{p}}$ is the pebble flux at 1 au and δt is the time interval for which the pebble flux is sustained in a cold disk. This can be achieved, for example, for $\dot{M}_{\mathrm{p}} \simeq 2 \times 10^{-6}\,M_{\mathrm{E}}\,\mathrm{yr}^{-1}$ **and** $f = 0.1$ **in mere** $\delta t = 10^5\,\mathrm{yr}$**.** The total water content in the Earth, however, is estimated to be equivalent to 2–8 Earth oceans[40], which would imply a proportionally longer timescale**.**

Our work makes several predictions for the structure and temperature profile of the protosolar disk. Assuming that the highlighted processes are not unusual, magnetic fields, disk winds and reversed surface density profiles should commonly be found in the inner regions of protoplanetary disks. Advanced 3-dimensional models can treat turbulence and viscosity in a self-consistent manner[22], but they do not have the ability to study effects on small spatial scales (as needed for migration of low-mass planets) and long time scales (as needed to understand the disk evolution). Adaptive-optics imaging instruments (e.g., Extremely Large Telescope) and long-baseline interferometric observatories (e.g., ALMA) will help to resolve the inner edges of protoplanetary disks and may eventually determine disk profiles on a sub-au scale. These efforts will be crucial for understanding the formation of worlds similar to our own, as well as their habitability.

Methods

Radiation-hydrodynamic model. Our system of 2D radiation hydrodynamic equations includes the continuity of gas, Navier–Stokes, gas energy, equation of state, continuity of pebbles, momentum of pebbles, accretion onto protoplanets, and equation of motion for protoplanets, with a detailed formulation given in **Supplementary Section A** (or in ref. [7]). Our code is a substantial modification of *Fargo*[41], with 20 source terms, including the viscous heating, stellar irradiation, vertical cooling, accretion heating, flux-limited diffusion approximation of the radiation transfer, solved by the successive overrelaxation method (SOR), two-fluid approximation, with a pressureless fluid for pebbles, pebble accretion in both the Bondi and Hill regimes, dynamic coupling between the pebble and gas disks, aerodynamic Epstein drag on pebbles and the corresponding back-reaction on gas, mutual gravity of the central body, protoplanets and gas disk, and vertical damping due to density waves[19].

Among the code improvements, we incorporated the Zhu opacity law[5] to better describe the radiative disk structure in the terrestrial region. Using Semenov opacities for dust[6] would result in a comparable structure, albeit a bit more complex, with even more evaporation lines. We corrected a mistake in our torque calculations (a minor shift of the sound speed field), which was pronounced in the terrestrial zone, and implemented an additional stabilisation of the SOR, which was needed close to the hot inner edge. Contrary to the disk in the giant-planet zone, where the pebble size is limited by radial drift, here it is limited by mutual collisions. We included a simple model for pebble evaporation. For completeness, we also included aerodynamic drag, which would be relevant mostly for asteroid-sized bodies. Optionally, a viscosity profile $\nu(r)$ or a temperature-dependent α viscosity can be used. We perform two relaxation procedures prior to the run: one with an outflow boundary condition and another with a damping. The time span of the simulations is computationally limited to $< 10^5\,\mathrm{yr}$, even though the algorithm is parallelized (MPI and OpenMP) and runs on $\simeq 100$ CPU cores.

N-body model. Our N-body model used to explore accretion on $\sim 10^7\,\mathrm{yr}$ timescales is based on *SyMBA*[25]. The symplectic algorithm preserves the total energy for a purely gravitational N-body system, handles close encounters between bodies by adaptively subdividing the time step, and efficiently detects and resolves collisions. A number of additional processes have been included from our hydrodynamic simulations. Hereinafter, we focus on the effect of migration, parameterized by its time scale $\tau(m)$, 0-torque radius $r_0(m)$, and migration rate $\dot{a}(a - r_0, \tau)$. These parameters are functions of protoplanet mass m. We include torque reductions for an increased eccentricity e, or the Lindblad torque reversal which is especially important in disks with low aspect ratios ($h = H/r \simeq 0.03$ in our case). Eccentricity and inclination damping, with the time scales τ_e and τ_i, is supplemented by hot-trail forcing, which sets the minimum values, denoted as e_hot and i_hot. In most simulations, we keep all these parameters constant, neglecting a potentially complex disk evolution. We consider them to either represent time-averaged values, or correspond to a disk (or a part of it) which was in steady state for a prolonged time. The effects were implemented as additional transversal, radial or vertical accelerations, and were inserted in the 'kick' term of the integrator (**Supplementary Section F**).

Initial conditions. There is a significant freedom in the selection of initial conditions, especially in terms of the surface density Σ. The assumption of minimum-mass solar nebula does *not* necessarily hold in the terrestrial zone if the terrestrial planets accreted a substantial part of their mass as pebbles or chondrules[18], originating at larger heliocentric distances and drifting inwards. Drifting pebbles can represent a larger source than solids formed *in situ*, as the total amount of solid material in the solar nebula is of the order $130\,M_{\mathrm{E}}$[2]. A filtering factor of individual terrestrial protoplanets, in other words, a fraction of inward-drifting solid material which is accreted by the planet, reaches a few per cent, depending on Σ and m.

At a later stage the disk must have been dissipating, with substantially lower Σ, and this may potentially produce a very interesting dynamics of the embedded protoplanets. For these reasons, we deliberately used disks with low Σ values, which are formally much less massive than the MMSN. On contrary, a more massive disk (as in [2]) would produce too much viscous heating and evaporation lines further out, unless the gas disk was actually less viscous.

Data availability The initial conditions of all simulations as well as selected snapshots of hydrodynamical simulations and data used to produce the respective figures are available at `http://sirrah.troja.mff.cuni.cz/~mira/fargo_terrestrial/`.

Code availability The code *Thorin* is publicly available at `http://sirrah.troja.mff.cuni.cz/~chrenko/` (and its specific version used in this study at the previous URL). The code *SyMBA* used in simulations is proprietary, but its specific part implementing additional accelerations is available.

1. Lambrechts, M. & Johansen, A. Rapid growth of gas-giant cores by pebble accretion. *Astron. Astrophys.* **544**, A32 (2012). 1205.3030.

2. Levison, H. F., Kretke, K. A. & Duncan, M. J. Growing the gas-giant planets by the gradual accumulation of pebbles. *Nature* **524**, 322–324 (2015). 1510.02094.

3. Wetherill, G. W. Formation of the earth. *Annual Review of Earth and Planetary Sciences* **18**, 205–256 (1990).

4. Chambers, J. E. & Wetherill, G. W. Making the Terrestrial Planets: N-Body Integrations of Planetary Embryos in Three Dimensions. *Icarus* **136**, 304–327 (1998).

5. Zhu, Z., Hartmann, L., Nelson, R. P. & Gammie, C. F. Challenges in Forming Planets by Gravitational Instability: Disk Irradiation and Clump Migration, Accretion, and Tidal Destruction. *Astrophys. J.* **746**, 110 (2012). 1111.6943.

6. Semenov, D., Henning, T., Helling, C., Ilgner, M. & Sedlmayr, E. Rosseland and Planck mean opacities for protoplanetary discs. *Astron. Astrophys.* **410**, 611–621 (2003). astro-ph/0308344.

7. Chrenko, O., Brož, M. & Lambrechts, M. Eccentricity excitation and merging of planetary embryos heated by pebble accretion. *Astron. Astrophys.* **606**, A114 (2017). 1706.06329.

8. Eklund, H. & Masset, F. S. Evolution of eccentricity and inclination of hot protoplanets embedded in radiative discs. *Mon. Not. R. Astron. Soc.* **469**, 206–217 (2017). 1704.01931.

9. Hauck, S. A. *et al.* The curious case of Mercury's internal structure. *Journal of Geophysical Research (Planets)* **118**, 1204–1220 (2013).

10. Morbidelli, A., Lunine, J. I., O'Brien, D. P., Raymond, S. N. & Walsh, K. J. Building Terrestrial Planets. *Annual Review of Earth and Planetary Sciences* **40**, 251–275 (2012). 1208.4694.

11. Hansen, B. M. S. Formation of the Terrestrial Planets from a Narrow Annulus. *Astrophys. J.* **703**, 1131–1140 (2009). 0908.0743.

12. Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P. & Mandell, A. M. A low mass for Mars from Jupiter's early gas-driven migration. *Nature* **475**, 206–209 (2011). 1201.5177.

13. Ogihara, M., Kokubo, E., Suzuki, T. K. & Morbidelli, A. Formation of the terrestrial planets in the solar system around 1 au via radial concentration of planetesimals. *Astron. Astrophys.* **612**, L5 (2018). 1804.02361.

14. Raymond, S. N., Izidoro, A., Bitsch, B. & Jacobson, S. A. Did Jupiter's core form in the innermost parts of the Sun's protoplanetary disc? *Mon. Not. R. Astron. Soc.* **458**, 2962–2972 (2016). 1602.06573.

15. Deienno, R., Walsh, K. J., Kretke, K. A. & Levison, H. F. Energy Dissipation in Large Collisions—No Change in Planet Formation Outcomes. *Astrophys. J.* **876**, 103 (2019).

16. Dauphas, N. & Pourmand, A. Hf-W-Th evidence for rapid growth of Mars and its status as a planetary embryo. *Nature* **473**, 489–492 (2011).

17. Levison, H. F., Kretke, K. A., Walsh, K. J. & Bottke, W. F. Growing the terrestrial planets from the gradual accumulation of sub-meter sized objects. *Proceedings of the National Academy of Science* **112**, 14180–14185 (2015). 1510.02095.

18. Johansen, A., Mac Low, M.-M., Lacerda, P. & Bizzarro, M. Growth of asteroids, planetary embryos, and Kuiper belt objects by chondrule accretion. *Science Advances* **1**, 1500109 (2015). 1503.07347.

19. Tanaka, H. & Ward, W. R. Three-dimensional Interaction between a Planet and an Isothermal Gaseous Disk. II. Eccentricity Waves and Bending Waves. *Astrophys. J.* **602**, 388–395 (2004).

20. Benítez-Llambay, P., Masset, F., Koenigsberger, G. & Szulágyi, J. Planet heating prevents inward migration of planetary cores. *Nature* **520**, 63–65 (2015). 1510.01778.

21. Kretke, K. A. & Lin, D. N. C. The Importance of Disk Structure in Stalling Type I Migration. *Astrophys. J.* **755**, 74 (2012). 1205.4014.

22. Flock, M., Fromang, S., Turner, N. J. & Benisty, M. 3D Radiation Nonideal Magnetohydrodynamical Simulations of the Inner Rim in Protoplanetary Disks. *Astrophys. J.* **835**, 230 (2017). 1612.02740.

23. Rafikov, R. R. Protoplanetary Disks as (Possibly) Viscous Disks. *Astrophys. J.* **837**, 163 (2017). 1701.02352.

24. Paardekooper, S.-J., Baruteau, C. & Kley, W. A torque formula for non-isothermal Type I planetary migration - II. Effects of diffusion. *Mon. Not. R. Astron. Soc.* **410**, 293–303 (2011). 1007.4964.

25. Duncan, M. J., Levison, H. F. & Lee, M. H. A Multiple Time Step Symplectic Algorithm for Integrating Close Encounters. *Astron. J.* **116**, 2067–2077 (1998).

26. Canup, R. M. *et al.* Origin of the Earth and Moon. *New Views of the Moon II* (2019).

27. Lambrechts, M. *et al.* Formation of planetary systems by pebble accretion and migration. How the radial pebble flux determines a terrestrial-planet or super-Earth growth mode. *Astron. Astrophys.* **627**, A83 (2019). 1902.08694.

28. Bitsch, B., Johansen, A., Lambrechts, M. & Morbidelli, A. The structure of protoplanetary discs around evolving young stars. *Astron. Astrophys.* **575**, A28 (2015). 1411.3255.

29. Brasser, R., Morbidelli, A., Gomes, R., Tsiganis, K. & Levison, H. F. Constructing the secular architecture of the solar system II: the terrestrial planets. *Astron. Astrophys.* **507**, 1053–1065 (2009). 0909.1891.

30. Clement, M. S., Kaib, N. A., Raymond, S. N. & Walsh, K. J. Mars' growth stunted by an early giant planet instability. *Icarus* **311**, 340–356 (2018). 1804.04233.

31. Elkins-Tanton, L. T. Magma Oceans in the Inner Solar System. *Annual Review of Earth and Planetary Sciences* **40**, 113–139 (2012).

32. Fischer, R. A. & Nimmo, F. Effects of core formation on the Hf-W isotopic composition of the Earth and dating of the Moon-forming impact. *Earth and Planetary Science Letters* **499**, 257–265 (2018).

33. Thiemens, M. M., Sprung, P., Fonseca, R. O. C., Leitzke, F. P. & Münker, C. Early Moon formation inferred from hafnium-tungsten systematics. *Nature Geoscience* **12**, 696–700 (2019).

34. Roig, F., Nesvorný, D. & DeSouza, S. R. Jumping Jupiter Can Explain Mercury's Orbit. *Astrophys. J.* **820**, L30 (2016). 1603.02502.

35. Asphaug, E. & Reufer, A. Mercury and other iron-rich planetary bodies as relics of inefficient accretion. *Nature Geoscience* **7**, 564–568 (2014).

36. Nittler, L. R., Chabot, N. L., Grove, T. L. & Peplowski, P. N. *The Chemical Composition of Mercury*, 30–51 (Cambridge Univ. Press, 2018).

37. Lyra, W., Paardekooper, S.-J. & Mac Low, M.-M. Orbital Migration of Low-mass Planets in Evolutionary Radiative Models: Avoiding Catastrophic Infall. *Astrophys. J. Lett.* **715**, L68–L73 (2010). `1003.0925`.

38. Morbidelli, A. *et al.* Fossilized condensation lines in the Solar System protoplanetary disk. *Icarus* **267**, 368–376 (2016). `1511.06556`.

39. Raymond, S. N. & Izidoro, A. Origin of water in the inner Solar System: Planetesimals scattered inward during Jupiter and Saturn's rapid gas accretion. *Icarus* **297**, 134–148 (2017). `1707.01234`.

40. Peslier, A. H., Schönbächler, M., Busemann, H. & Karato, S.-I. Water in the Earth's Interior: Distribution and Origin. *Space Sci. Rev.* **212**, 743–810 (2017).

41. Masset, F. FARGO: A fast eulerian transport algorithm for differentially rotating disks. *Astron. Astrophys. Suppl. Ser.* **141**, 165–173 (2000). `astro-ph/9910390`.

Acknowledgements The work of M.B. and O.C. has been supported by the Grant Agency of the Czech Republic (grant no. 18-06083S). The work of O.C. has been supported by Charles University (research program no. UNCE/SCI/023). D.N.'s work was supported by the NASA SSERVI and XRP programs. Computational resources were supplied by the project "e-Infrastruktura CZ" (e-INFRA LM2018140) provided within the program Projects of Large Research, Development and Innovations Infrastructures. We are grateful to W. F. Bottke and A. Morbidelli for valuable discussions. We thank R. Fischer for sharing her geochemical computations with us. **We also thank three anonymous referees for constructive and insightful comments.**

Author Contributions All authors conceived and designed the experiments, O.C. and D.N. contributed analysis tools and performed some of the experiments, M.B. and N.D. analyzed the data, M.B. and D.N. wrote the paper.

Competing Interests The authors declare that they have no competing financial interests.

Correspondence Correspondence and requests for materials should be addressed to M.B.
(email: mira@sirrah.troja.mff.cuni.cz).

Figure 1: Radiation-hydrodynamic model of the terrestrial planet zone with Mercury- to Mars-size protoplanets migrating in a gas disk. Here we adopted an MRI-active disk with the viscosity $\nu(r)$ prescribed as a function of radial distance r. The corresponding values of the α parameter, often used to describe the viscosity, would be in the range 0.001 to 0.01. To emphasize gas density perturbations induced by the protoplanets, here we plot $(\Sigma - \Sigma(r))/\Sigma(r)$, where Σ is the local surface density and $\Sigma(r)$ is the azimuthally averaged surface density at radius r. This effectively removes the global radial dependence of Σ and highlights structures at the Lindblad resonances and corotation regions, which drive planetary migration. The total mass of the protoplanets was set to $2\,M_{\rm E}$.

Figure 2: Convergent migration toward $\sim 1\,\mathrm{au}$ is illustrated for Mercury- to Earth-mass protoplanets. The migration rates, $\mathrm{d}a/\mathrm{d}t$, were computed from hydrodynamical simulations (see Figure 1), which include the Lindblad, corotation and heating torques, and from semianalytical formulae[24]. Panel (a) shows $\mathrm{d}a/\mathrm{d}t$ as a function of protoplanet's semimajor axis a and mass m. **Colours correspond to the migration rate (orange positive, blue negative).** The convergence radius in (a) slightly increases with mass. The characteristic values of $|\mathrm{d}a/\mathrm{d}t|$ are $\sim 10^{-7}$–$10^{-6}\,\mathrm{au\,yr^{-1}}$, which implies long-range orbital drift in the disk lifetime. Panel (b) shows extrapolated evolutions $a(t)$ for Mercury- to Mars-size protoplanets from our hydrodynamical simulations. **Circles correspond to the initial and final positions of protoplanets.**

Figure 3: Convergent migration leads to a compact configuration of orbits that matches the orbital architecture of the terrestrial planet system. Panel (a) shows **the final mass** m **vs. the semimajor axis** a **for** a statistical ensemble **of** 50 individual simulations (gray circles) Each simulation starts with Mercury- to Mars-size protoplanets. The protoplanetary disk lifetime is assumed to be $10^7\,\mathrm{yr}$. Three to six terrestrial planets typically form in these simulations with more massive planets near the convergence radius and less massive planets near borders of the convergence zone (see **Supplementary Section D** for an in-depth analysis of the results). **One successful simulation is emphasized (circles filled by colour).** The terrestrial planets are shown for reference (green circles). Panel (b) shows **the temporal evolution** $a(t)$ **for the** successful simulation. The symbol sizes are proportional to planet mass. The horizontal line segments in (a) and grey lines in (b) express the radial excursions of planets on their orbits (i.e., measure the orbital eccentricity, e).

Figure 4: Temperature profile of the protoplanetary disk determines the local chemical composition of solids, whereas temperature perturbations affect the orbital evolution of protoplanets. Panel (a) shows the temperature profile $T(r)$ for our nominal disk with $\Sigma_0 = 750\,\mathrm{g\,cm^{-2}}$ (solid violet line), and for a dissipating disk with $\Sigma_0 = 75\,\mathrm{g\,cm^{-2}}$ (dashed blue line). The evaporation temperature of metallic iron and Mg-rich silicates, $T_{\mathrm{ev}} \simeq 1500\,\mathrm{K}$, is indicated by the horizontal orange strip, **together with the corresponding range of r.** The present-day terrestrial planets are indicated by gray circles at the bottom of panel (a). Panel (b) shows the temperature perturbations $\delta T = T - T(r)$ in the dissipating disk, which arise due to accretion heating ($\delta T > 50\,\mathrm{K}$ for a Venus-size body). The hot-trail effect (see hot regions behind protoplanets following their epicyclic motion) can increase the orbital eccentricity up to $e \simeq 0.02$. Here we highlight a case where, in addition to Mercury, Venus and Mars, two planets with $M = 0.5\,M_{\mathrm{E}}$ were placed near 1 au. This represents one of the possible configurations that may have triggered the Moon-forming impact[26].