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

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The massive cores of the giant planets are thought to have formed in a gas disk by the accretion of pebble-sized particles whose accretional cross-section was enhanced by aerodynamic gas drag. 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-sized protoplanets. Here we propose, instead, that the terrestrial planets of the Solar System formed earlier by the gas-driven convergent migration of protoplanets towards ~1 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. 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. 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 1,500 K inside 0.4 au, implying that Mercury grew in a highly reducing environment. Mercury’s bulk composition is consistent with the Earth mass, initially located in an annulus 0.4–1.8 au (Fig. 1). Our fiducial gas disk model is defined by the radial gas flux and the kinematic viscosity of the gas, which is a function of the gas density profile. In particular, $M = 10^{-8} M_{\odot}$ yr$^{-1}$, $v(r) = 1.1 \times 10^{14}$ cm$^2$ s$^{-1}$ ($r/1$ au)$^4$, where the exponent smoothly changes with $r$, from $s_i = -2$ to $s_i = 0.5$. The resulting $\Sigma(r)$ radially increases across the inner portion of the terrestrial zone, $r \leq 1$ au, and decreases further out. Such a $\Sigma(r)$ profile is motivated by studies of disks with magneto-rotational instability, active layers or disk winds. Here we focus on viscous disks and local scales (~1 au), although on a global scale transport could be inviscid (as discussed by ref. 13). The gas temperature $T$ and disk aspect ratio $h = H/r$ are controlled by the opacity $\kappa(p, T)$ (ref. 14), where $p$ is the gas density. The pebble disk is defined by the pebble flux $M_\text{p}$ at the outer boundary. All of these components affect the migration of protoplanets. See Methods and Supplementary 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 $a$. Our simulations found that protoplanets with $a > 1$ au migrate inwards and protoplanets with $a < 1$ au migrate outwards. The absolute value of the torque generally scales as $\Gamma = (g/h) \Sigma(r) \Omega^2$, where $q = m/M_\text{p}$ is the planet-to-Sun mass ratio and $\Omega$ the Keplerian angular velocity, but its precise value and sign depend on 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 may reduce and reverse if the eccentricity is excited to $e \gtrsim 2h$, for example during close encounters between protoplanets. A semi-analytical expression from ref. 24 reveals its dependence on the slopes of $\gamma$, $\beta$ of the gas disk profiles,

$\Gamma_l = \Gamma_0 \gamma_{\text{eff}} \left( -2.5 - 1.7 \beta + 0.1 \alpha \right) (0.4 h/b_\text{sm})^{0.71}; b_\text{sm} = r_{\text{sm}}/(hr),$  

where $r_{\text{sm}}$ denotes the smoothing length and $\gamma_{\text{eff}}$ the effective adiabatic index. The corotation torque is related to gas moving along horseshoe-like orbits. It becomes positive for certain slopes of $\Sigma$ and $T$. If it is kept unsaturated, by non-zero viscosity for example, the corresponding expression is

$\Gamma_c = \Gamma_0 \gamma_{\text{eff}} \left( [1.5 - \alpha - 2 \xi \gamma_{\text{eff}}] (0.4 h/b_\text{sm})^{1.26} + 2.2 \xi (0.4 h/b_\text{sm})^{0.71} \right),$  

where $\xi \equiv \beta - (\gamma - 1) \alpha$ is the slope of entropy $S(r)$. The heating torque 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

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and (4) collisions between similar-sized protoplanets are relatively common (see also ref. 21). The system architecture is established by collisions, differential migration and eccentricity damping21, 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 of $\dot{M}_p = 2 \times 10^{-6} M_\odot$ yr$^{-1}$, the growth is roughly equally contributed by pebbles and protoplanet mergers. Substantially larger pebble fluxes sustained over millions of years would lead to planet overgrowth (that is, formation of super Earths; see ref. 2) and would weaken radial mass concentration. A more systematic sampling of model parameters could help to ‘reverse engineer’ the disk conditions and lifetime.

The heart of our argument is that 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 planets11. This new model offers a notable advantage over the previously suggested mechanisms of annulus truncation12 because: (1) convergent migration confines the annulus from both sides, and (2) Venus and Earth are kept within the convergence zone, avoiding problems with their repulsion and weakening of the radial mass concentration11.

A gas disk nearing the end of its lifespan is expected to be rarified by viscous spreading/photoevaporation, and consequently cold23. To study the orbital behaviour 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, $\Sigma = 750$ g cm$^{-2}$ at 1 au. For this set of simulations, we used power-law profiles $\Sigma(r)$, with a slope similar to that in the Minimum Mass Solar Nebula. The terrestrial planets were assumed to be almost formed and close to their present orbital radii. A pebble accretion flux up to $\dot{M}_p \approx 2 \times 10^{-6} M_\odot$ yr$^{-1}$ (corresponding to the heating power $L \approx 10^{20}$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 (for example when $\Sigma > \Sigma_c$). Additional heating can be provided by planetesimals, mergers, internal differentiation and radioactivity. Notably, we found
that the planetary orbits became excited by the hot-trail effect\(^7\textsuperscript{,}^8\), which arises due to pebble accretion on protoplanets, release of their kinetic energy and radiative heating of neighbouring gas (Fig. 4). It is especially effective for values of \(\Sigma\) approximately 10 times lower, when the thermal capacity of gas is lower but its gravity still substantial. As a result, the orbital eccentricities of planets evolve towards asymptotic values \(\approx 0.015 \text{--} 0.02\) and migrating planets avoid capture in orbital resonances. The hot-trail effect can even explain the current orbital eccentricities of Venus and Earth (proper \(e = 0.02\) and 0.01, respectively). Additional changes may have been inflicted in the terrestrial planet system by gravitational perturbations during migration/instability of the giant planets\(^2\textsuperscript{,}^3\textsuperscript{,}^4\textsuperscript{,}^5\), although these often lead to over-excitation.

A strict version of this work’s main thesis—that the terrestrial planets formed early—would imply that the Moon-forming impact occurred early as well \(t_{\text{Moon}} < 10\text{ Myr}\). Lunar magma ocean solidification may have occurred much later, because the lunar magma ocean may have been sustained by tidal heating for hundreds of millions of years\(^6\). However, for \(t_{\text{Moon}} < 10\text{ Myr}\), geochemical modelling of the Hf–W system (refs.\(^3\textsuperscript{,}^5\) and Supplementary Section H) shows that the tungsten anomaly in the mantle of Earth would be generally higher than the observed value, \(\varepsilon_{\text{WO}} = 1.9 \pm 0.1\). We therefore prefer our simulations with SyMBA that ended with five (or more)

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**Fig. 4** The temperature profile of the protoplanetary disk determines the local chemical composition of solids, whereas temperature perturbations affect the orbital evolution of protoplanets. **a.** \(T(r)\) for our nominal disk with \(\Sigma_0 = 750\text{ g cm}^{-2}\) and for a dissipating disk with \(\Sigma_0 = 75\text{ g cm}^{-2}\). The evaporation temperature of metallic iron and Mg-rich silicates, \(T_e = 1,500\text{ K}\), is indicated by the horizontal orange bar, together with the corresponding range of \(r\). The present-day terrestrial planets are indicated by grey circles, and their radial excursions by horizontal grey bars, at the bottom of the panel. **b.** Temperature perturbations \(\delta T = T - T(r)\) in the dissipating disk, which arise due to accretion heating \(\delta T > 50\text{ K}\) for a Venus-sized body. The hot-trail effect (the hot regions behind protoplanets following their epicyclic motion) can increase the orbital eccentricity up to \(e \approx 0.02\). Here we highlight a case where, in addition to Mercury, Venus and Mars, two planets with \(M = 0.5\text{ }M_e\) were placed near 1 au. This represents one of the possible configurations that may have triggered the Moon-forming impact\(^7\textsuperscript{,}^8\). The hot-trail effect is shown in Supplementary Video 3.
terrestrial protoplanets, thus leaving space for a late Moon-forming impact and \( f_{\text{EMLY}} \) 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, \( T_{\text{ev}} \), of many minerals. As solids evaporate at the critical radius \( r_{\text{ev}} \), 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 Fig. 4 reach \( T \approx 1,500 \) K and create a highly reducing environment in which pebbles drift from larger radii\(^{\text{35}}\) down to \( r_{\text{ev}} \approx 0.4 \) au. The evaporation of pebbles alters the local chemical composition of the gas. This is very different from previous nebular hypotheses that 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\(^{36}\) and relax constraints on the hypothesized impact-related removal of the silicate mantle\(^{37}\). 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\(^{38}\). As the temperature decreases in a low-mass, late-stage disk (Fig. 4), moderately volatile elements (such as Na, S, K, Cl) could have been delivered by pebbles to Mercury’s surface, as late-stage disk (Fig. 4), moderately volatile elements (such as Na, S, K, Cl) could have been delivered by pebbles to Mercury’s surface, as needed to explain its non-negligible volatile budget\(^{38}\).

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 \( \sim 1 \) au (refs. \(^{39,40}\)). This could create the right conditions for water delivery to the Earth if the flux of icy/hydrated pebbles from >3 au remained sufficiently high for a sufficiently long period. Given the D/H ratio of the ocean water (1.5 \times 10\(^{-5}\)), the best match among existing reservoirs is carbonaceous chondrites. However, the importance of this process would diminish if Jupiter and Saturn totally block the flux of icy pebbles from >3 au (ref. \(^{41}\)), and an alternative delivery by planetesimals is more likely\(^{42}\). For comparison, we calculate that the Earth would accrete \( \sim 1-1.5 \)% of pebbles moving past 1 au. To deliver 1 Earth ocean worth of water (2.3 \times 10\(^{-4}\) \( M_\oplus \)), we would need \( f_{\text{MPL}} \delta \tau \sim 0.02 M_\oplus \), where \( 0 < f < 1 \) is the mass fraction of water in pebbles, \( M_\oplus \) is the pebble flux at 1 au and \( \delta \tau \) is the time interval for which the pebble flux is sustained in a cold disk. This can be achieved, for example, for \( f_{\text{MPL}} \approx 2 \times 10^{-6} M_\oplus \) yr\(^{-1}\) and \( f=0.1 \) in mere \( \delta \tau = 10^4 \) yr. The total water content in the Earth, however, is estimated to be equivalent to 2–8 Earth oceans\(^{42}\), 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 three-dimensional models can treat turbulence and viscosity in a self-consistent manner\(^{43}\), but they do not have the ability to study effects on small spatial scales (as needed to model the migration of low-mass planets) and long timescales (as needed to understand disk evolution). Adaptive-optics imaging instruments (such as the Extremely Large Telescope) and long-baseline interferometric observatories (ALMA, for example) will help to resolve the inner edges of protoplanetary disks and may eventually determine disk profiles on a sub-astronomical-unit scale. These efforts will be crucial for understanding the formation of worlds similar to our own, as well as their habitability.

Methods
Radiative-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 equations 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\(^{44}\), 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 Photon–Cloud method, 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\(^{41}\).

Among the code improvements, we incorporated the Zhu opacity law\(^{45}\) to better describe the radiative disk structure in the terrestrial region. Using Semenov opacities for dust 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 stabilization of the successive over-relaxation method, 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 important mostly for asteroid-sized bodies. An optional viscosity profile \( \nu \) or a temperature-dependent \( \alpha \) viscosity can also be used. We perform two relaxation procedures before the run: one with an outflow boundary condition and another with damping. The time span of the simulations was computationally limited to \( \leq 10^7 \) yr, even though the algorithm is parallelized (MPI and OpenMP) and runs on \( \approx 100 \) CPU cores.

N-body model. Our N-body model used to explore accretion on \( \leq 10^7 \) 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 timescale \( \tau(n)\), 0-torque radius \( r_0(m)\) and migration rate \( \dot{a}(a \sim r_\text{in}, \tau)\). 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 (\( h = H/r < 0.03 \) in our case). Eccentricity and inclination damping, with the timescales \( \tau_e \) and \( \tau_I \) are supplemented by hot-trail forcing, which sets the minimum values, denoted as \( \epsilon_{\text{min}} \) and \( \dot{\epsilon}_{\text{min}} \). 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) that 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 freedom in the selection of initial conditions, especially in terms of \( \Sigma \). The assumption of a 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 in the order of 130 \( M_\oplus \) (ref. \(^{1}\)). A filtering factor of individual terrestrial protoplanets (in other words, a fraction of inward-drifting solid material that is accreted by the planet) reaches a few per cent, depending on \( \Sigma \) and \( m \).

At a later stage, the disk must have been dissipating, with substantially lower \( \Sigma \), and this may potentially produce a very interesting dynamics of the embedded protoplanets. For these reasons, we deliberately used disks with low \( \Sigma \) values, which are formally much less massive than the Minimum Mass Solar Nebula. On contrary, a more massive disk (as in ref. \(^{7}\)) 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
Thorin is publicly available at http://sirrah.troja.mff.cuni.cz/~cherenko/ (and its specific version used in this study at the previous URL). SyMBA, used in simulations, is proprietary, but its specific part implementing additional accelerations is available.

Received: 26 September 2019; Accepted: 29 April 2021; Published online: 5 July 2021

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Acknowledgements
The work of M.B. and O.C. was supported by the Grant Agency of the Czech Republic (grant numbers 18–06083S). The work of O.C. was supported by Charles University (research programme number UNT2/SCI/023). The work of D.N. was supported by the NASA SSERVI and XRP programmes. Computational resources were supplied by the project ‘-Infrastruktura CZ’ (e-INFRA LM2018140) provided within the programme 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.

Author contributions
All authors conceived and designed the numerical experiments. O.C. and D.N. analysed the data. M.B. and D.N. wrote the paper.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41550-021-01383-3.

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Peer review information Nature Astronomy thanks Elena Lega and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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