

Terrestrial planet formation by torque-driven convergent migration of planetary embryos

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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 roughly Mars-size protoplanets³. Here we propose, instead, that the terrestrial planets formed earlier by gas-driven convergent migration of protoplanets toward ~ 1 au (related ref. ⁴ invoked a different process to concentrate planetesimals). To investigate situations in which convergent migration occurs, we developed a radiation-hydrodynamic model with realistic opacities^{5,6} to determine the thermal structure of the gas and pebble disks in the terrestrial planet zone. We find that protoplanets rapidly grow 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 terrestrial planet 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 proto-

solar 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 composition⁹. In a late-stage cold gas disk, accretion of icy/hydrated pebbles would contribute to Earth's water budget.

In the standard model of the terrestrial planet formation¹⁰, accretional collisions between ~ 1 to 100km planetesimals lead to gradual build up of lunar- to Mars-size protoplanets, which gravitationally interact and further grow during a *late* stage of giant impacts³. Indeed, radiometric data indicate that the Moon-forming impact on proto-Earth¹¹ probably happened relatively late, some 50 Myr or more after the appearance of the first solar system solids¹². Computer simulations of late-stage accretion are required to match various constraints¹³, including the similar semimajor axes of Venus and Earth (only $\simeq 0.3$ au radial separation). The results indicate that the terrestrial planets should have accreted from a narrow annulus (0.7–1 au)¹⁴, perhaps because the planetesimal disk was truncated at ~ 1 au by Jupiter's inward and then outward migration¹⁵. The cause behind the suggested inner edge at 0.7 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 drag⁴, **or removal of planetesimals by outward-migrating giant planet core**¹⁶. 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 au¹⁷. Moreover, the early growth of terrestrial protoplanets may have been regulated by efficient accretion of small, pebble-size particles^{18,19}, rather than larger planetesimals. 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 around²⁰.

Gas-driven migration is critically important for protoplanets²¹. We constructed a radiation-hydrodynamic model of gas and pebble disks to study migration in the terrestrial planet zone. In our model, hereafter named *Thorin*⁷, protoplanets migrate due to several gravitational torque terms (Lindblad, corotation and heating²²). 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_E , where $M_E = 6 \times 10^{24}$ kg is the Earth mass), initially located in **an annulus 0.4–1.8 au** (Figure 1). Our fiducial gas disk model²³ is defined by the radial gas flux \dot{M} and kinematic viscosity $\nu(r)$, which is a function of radius r . **In particular, $\dot{M} = 10^{-8} M_\odot \text{yr}^{-1}$, $\nu(r) = 1.1 \times 10^{14} \text{cm}^2 \text{s}^{-1} (r/1 \text{au})^s$, 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, $r \lesssim 1 \text{au}$, and decreasing further out. Such a $\Sigma(r)$ inversion is motivated by studies disks with magneto-rotational instability (MRI)²⁴, active layers²³, or disk winds⁴. Here we focus on viscous disks and local scales ($\sim 1 \text{au}$), although on a global scale transport could be inviscid (as discussed by ref. ²⁵). 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}_p at the outer boundary. All these components affect migration of protoplanets. See Methods and the supplementary information (SI) 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)²⁶. We found that protoplanets with $a > 1 \text{au}$ migrate inward and protoplanets with $a < 1 \text{au}$ migrate outward. The absolute value of the torque generally scales as $\Gamma_0 = (q/h)^2 \Sigma r^4 \Omega^2$, where $q = m/M_S$ 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 ²⁶ reveals its dependence on the slopes α , β of Σ , T profiles, $\Gamma_L = \Gamma_0/\gamma_{\text{eff}}(-2.5 - 1.7\beta + 0.1\alpha)(0.4h/b_{\text{sm}})^{0.71}$; $b_{\text{sm}} = r_{\text{sm}}/(hr)$, 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 expression²⁶ is $\Gamma_c = \Gamma_0/\gamma_{\text{eff}}[(1.5 - \alpha - 2\xi/\gamma_{\text{eff}})(0.4h/b_{\text{sm}})^{1.26} + 2.2\xi(0.4h/b_{\text{sm}})^{0.71}]$, where $\xi \equiv \beta - (\gamma - 1)\alpha$ is the slope of entropy $\mathcal{S}(r)$. The heating torque²² 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 $r_c \simeq 1$ au. **In fact, r_c was likely moving in the course of time, but hereinafter we assume it ended up at 1 au.** The characteristic migration rates computed numerically by our RHD model are $da/dt \simeq \pm 10^{-7}$ to 10^{-6} au yr⁻¹. The protoplanets are therefore expected to move near r_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 SI.

We performed long-term accretional simulations with a symplectic N-body integrator called *SyMBA*²⁷ 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^{7,8,21}, was informed from our hydrocode simulations described above and mimicked by additional acceleration terms in *SyMBA* (Methods). Specifically, the migration rate da/dt was set as a function of planet mass and orbit (from Figure 2 and similar results that we obtained for other disk models; SI). 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 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 also¹¹). 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 $\dot{M}_p = 2 \times 10^{-6} M_E \text{ yr}^{-1}$, 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.²⁸) 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 planets¹⁴. This new model offers a notable advantage over the previously suggested mechanisms of annulus truncation¹⁵, 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**¹⁷.

A gas disk nearing the end of its lifespan is expected to be rarefied by viscous spreading/photoevaporation, and consequently cold²⁹. 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, $\Sigma_0 = 750 \text{ g cm}^{-2}$ 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 $\dot{M}_p \simeq 2 \times 10^{-4} M_E \text{ yr}^{-1}$ (**corresponding to the heating power $L \simeq 10^{20}$ 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 (when $\Sigma_p \gtrsim \Sigma$).** **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 ~ 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 planets³⁰, **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 ($t_{\text{Moon}} < 10 \text{ Myr}$). Lunar Magma Ocean (LMO) solidification may have occurred much later, because the LMO may have been sustained by tidal heating for hundreds of million years³¹. However, for $t_{\text{Moon}} < 10 \text{ Myr}$, geochemical modeling of the Hf/W system (ref. ^{12,32} and SI) shows that the tungsten anomaly in the mantle of Earth would be generally higher than the observed value, $\varepsilon_{182\text{W}} = 1.9 \pm 0.1$. 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 $\varepsilon_{182\text{W}}$ decrease through equilibration. A late impact could have spontaneously occurred in a dynamically unstable terrestrial system or been triggered by outer planet migration/instability³³.

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 $T \simeq 1500 \text{ K}$ and create a highly reducing environment in which pebbles drift from larger radii¹⁹ down to $r_{\text{ev}} \sim 0.4 \text{ au}$. 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 Mercury⁹ and relax

constraints on the hypothesized impact-related removal of the silicate mantle³⁴. 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 gas³⁵. 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 budget³⁵.**

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 ~ 1 au²⁹. 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 sufficiently long time. For reference, we calculate that the Earth would accrete 1–1.5% of pebbles moving past 1 au. To deliver 1 Earth ocean worth of water ($2.3 \times 10^{-4} M_E$), we would need that $f \dot{M}_p \delta t \sim 0.02 M_E$, where $0 < f < 1$ is the mass fraction of water in pebbles, \dot{M}_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 $\dot{M}_p \simeq 2 \times 10^{-6} M_E \text{ yr}^{-1}$ and $f = 1$ in mere $\delta t = 10^4$ yr. The total water content in the Earth, however, is estimated to be equivalent to 2–8 Earth oceans³⁶, which would imply a proportionally longer timescale or other delivery methods¹⁵. **Given the D/H ratio of the ocean water (1.5×10^{-4}), the best match among existing reservoirs are carbonaceous chondrites. However,** the importance of this process would diminish if Jupiter and Saturn **totally** block the flux of icy pebbles from > 5 au³⁷.

Our work makes several predictions for the structure and temperature profile of the proto-solar 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 manner²⁴, 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 the SI (or in ref. ⁷). Our code is a substantial modification of *Fargo*³⁸, 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 pressure-less 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 waves²¹.

Among the code improvements, we incorporated the Zhu opacity law⁵ to better describe the radiative disk structure in the terrestrial region. Using Semenov opacities for dust⁶ 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 $< 10^5$ 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 $\sim 10^7$ yr timescales is based on *SyMBA*²⁷. 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 (SI).

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 chondrules¹⁹, 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 $130 M_{\text{E}}^2$. 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>.

mf.f.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.

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