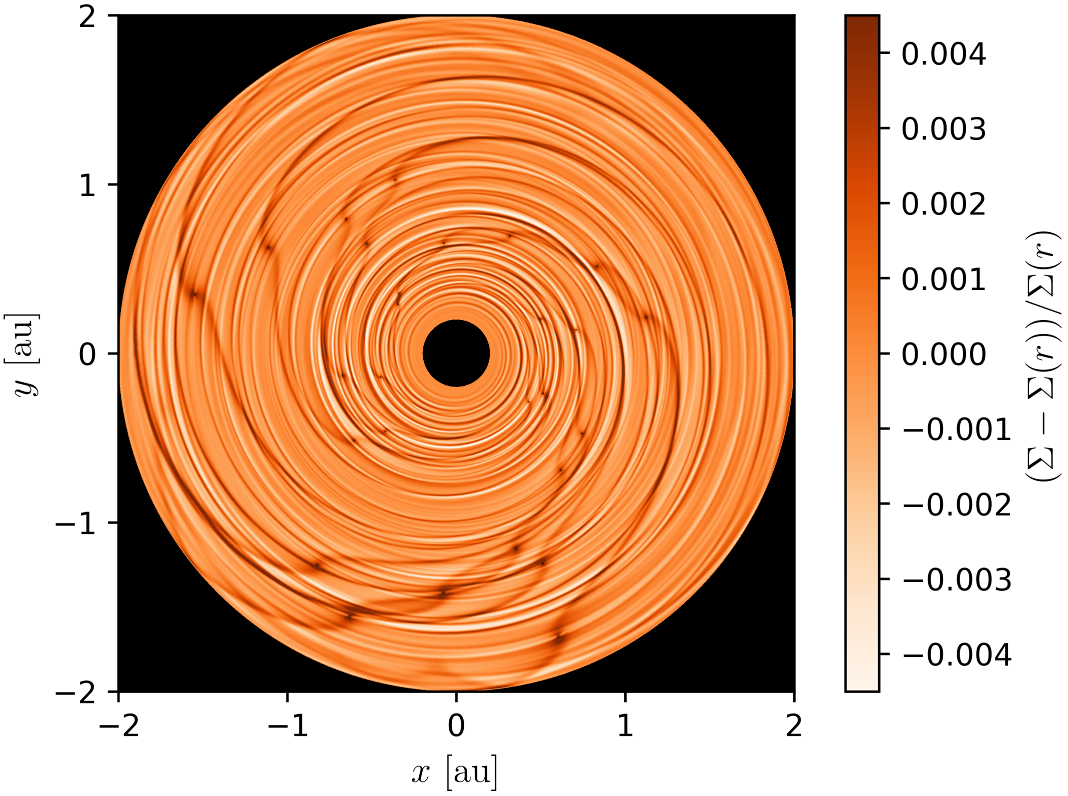
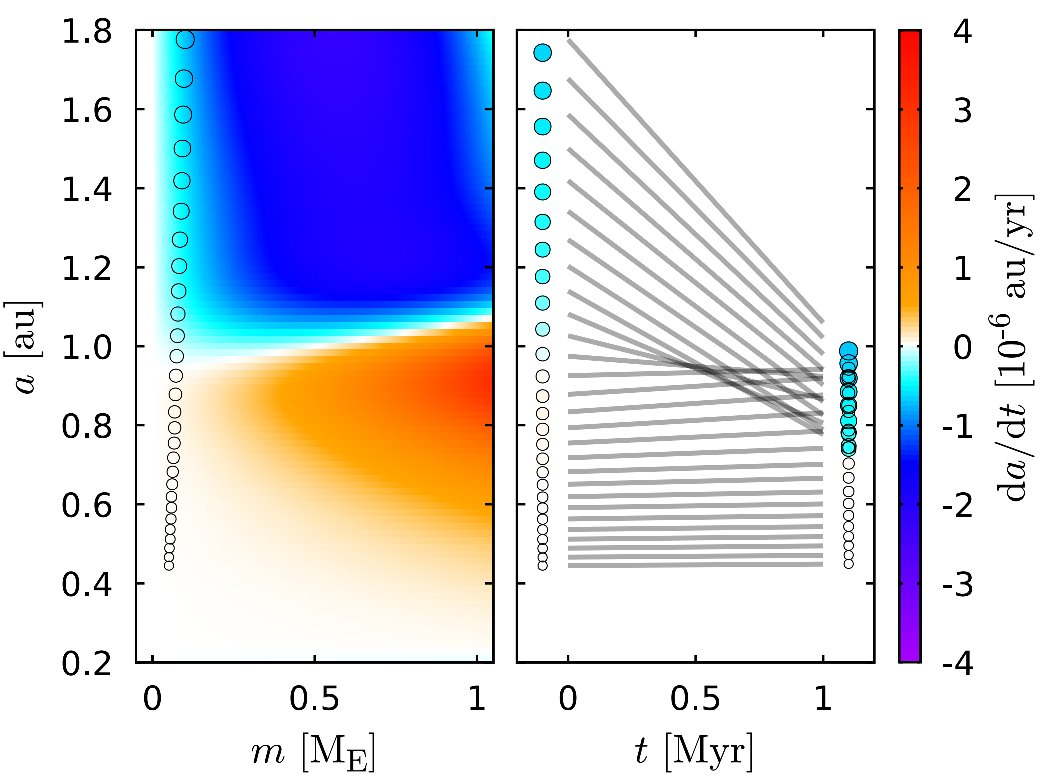
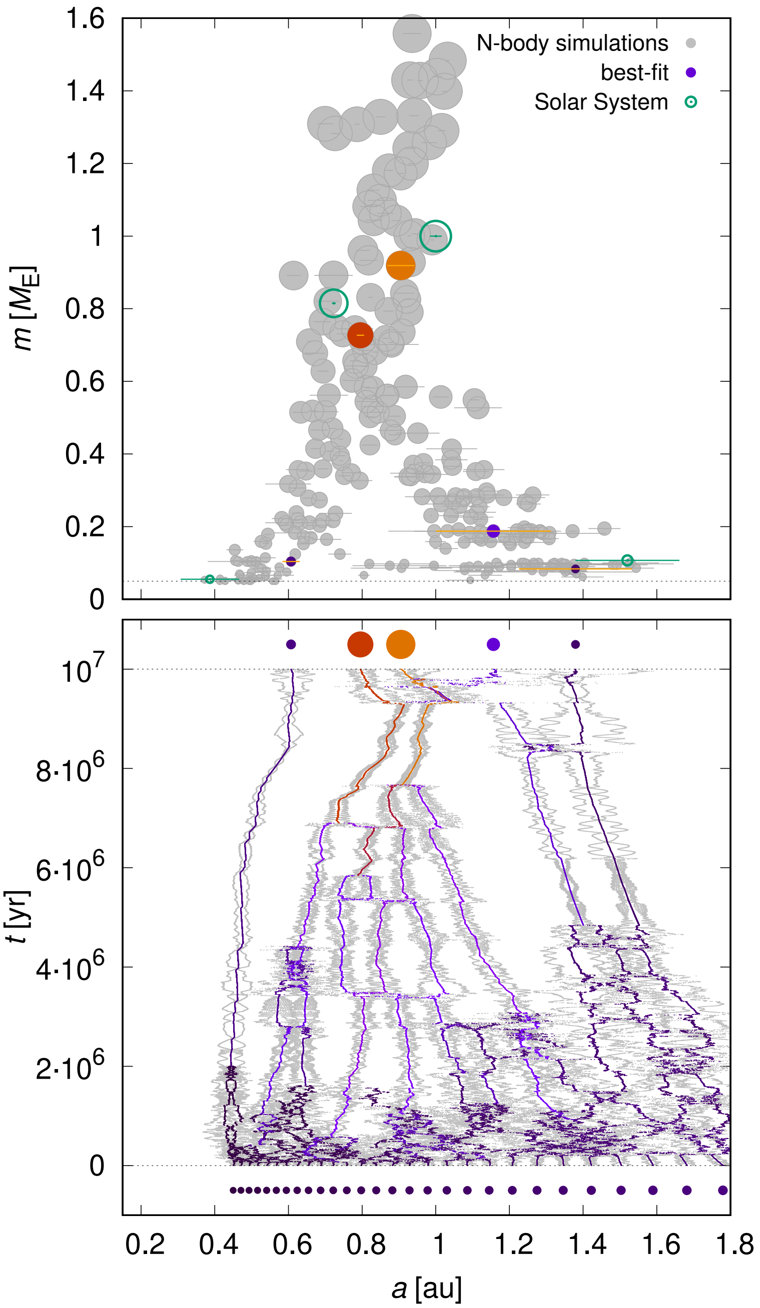
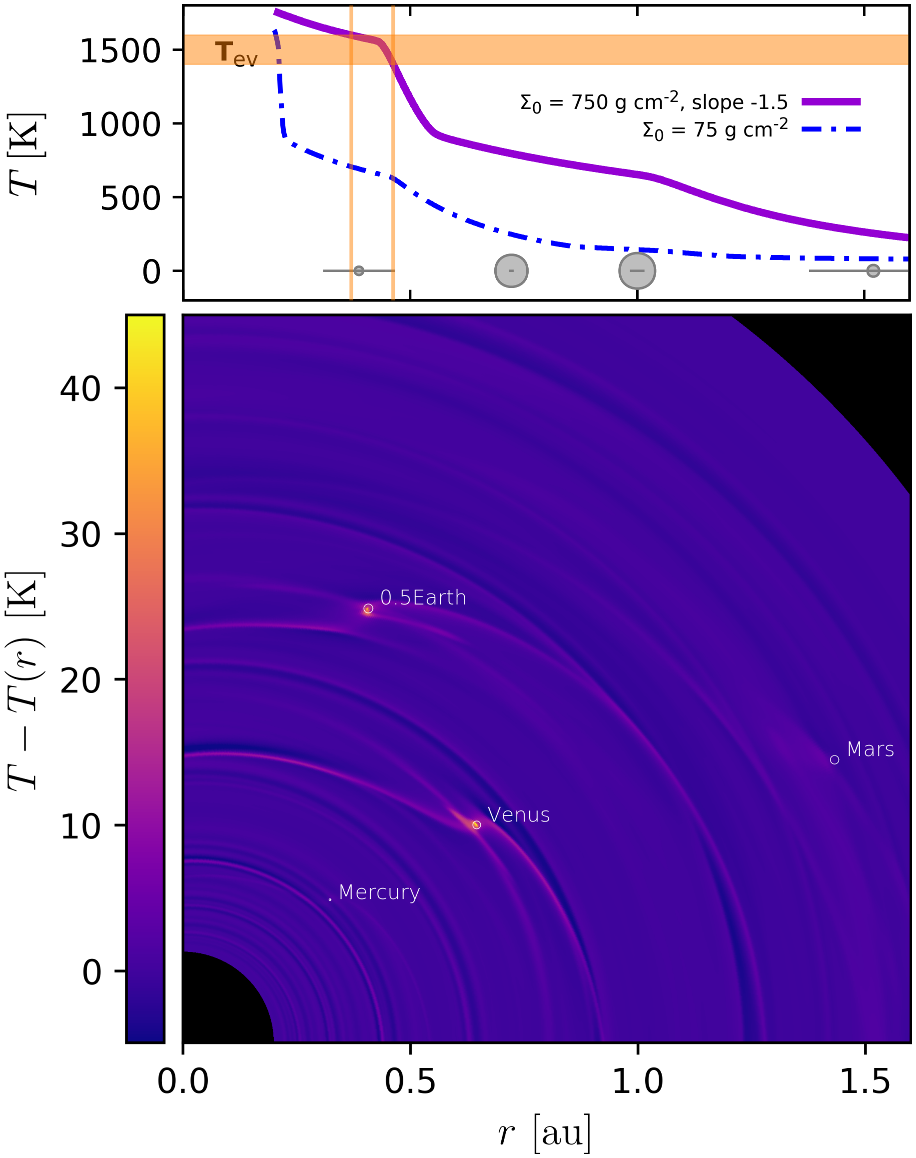


2
1
0
−1
−2
y [au]
−2
−1
0
1
2
x [au]
0.004
0.003
0.002
0.001
0.000
−0.001
−0.002
−0.003
−0.004
$(\Sigma - \Sigma(r))/\Sigma(r)$



1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
a [au]
0
0.5
1
m [$\mathrm{M_E}$]
0
0.5
1
t [Myr]
4
3
2
1
0
-1
-2
-3
-4
$\mathrm{d}a/\mathrm{d}t$ [10^{-6} au/yr]


N-body simulations
best-fit
Solar System
m [M_E]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
t [yr]
10^7
8·10^6
6·10^6
4·10^6
2·10^6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
a [au]



1500
1000
500
0
T [K]
$\mathbf{T}_{ev}$
Σ_0 = 750 g cm^{-2}, slope -1.5
Σ_0 = 75 g cm^{-2}
40
30
20
10
0
$T - T(r)$ [K]
0.5Earth
Venus
Mercury
Mars
0.0
0.5
1.0
1.5
r [au]

1. 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`.
2. Canup, R. M. *et al.* Origin of the Earth and Moon. *New Views of the Moon II* (2019).

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 $2\,M_{\mathrm{E}}$.

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[1]. Panel (a) shows $\mathrm{d}a/\mathrm{d}t$ as a function of protoplanet's semimajor axis a and mass m. 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.

Figure 3 Convergent migration leads to a compact configuration of orbits that matches the orbital architecture of the terrestrial planet system. Panel (a) shows a statistical ensemble of results from 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 SI for an in-depth analysis of the results). The terrestrial planets are shown for reference (green circles). Panel (b) shows one 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. 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[2].