Dynamical tides affect the evolution timescale of super Earth

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What is super Earth?

1. Mass of solid core: $2 \sim 20 M_{\oplus}$
2. Core radius: $1 \sim 2 R_{\oplus}$
3. Gas-to-core mass ratios (GCRs): up to 10% (Earth:$\sim 10^{-6}$)
4. Bulk densities: $< 3 \mathrm{gcm}^{-3}$

Just as we see from the above, we have no strict definition of super-Earth. To be exact, we just assemble some exoplanets whose parameters are in the range that the above list, and give them a name super-Earths. Super means more massive than Earth, Earth suggests that they are rocky exoplanets, not gas giants. More details see[1]

[1] Eve J. Lee and Eugene Chiang. "To cool is to accrete: analytic scalings for nebular accretion of planetary atmospheres". In: *Astrophysical Journal* 811.1 (2015), p. 41. arXiv: 1508.05096.

The puzzle of the super Earth.

The atmosphere of Earth has been outgassed from the rock. However, the GCRs of super-Earths are too large to been explained by the outgassing process. More plausibly, super-Earth atmospheres originated by accretion from the primordial nebula, which is just as Jupiter did. Since the core mass of Jupiter is in the range of $10 \sim 20M_{\bigoplus}$, so why the super-Earths escaped from becoming a gas giant?

Two categories of the models of gas giant.

Models of giant planet formation fall into two categories: core accretion or gravitational instability[2].

1. Gravitational instability
   Investigate the fragmentation of the protoplanetary disk into bound clumps.
2. Core accretion
   A solid core grows until it becomes massive enough to rapidly accrete gas.

My work is based on the Core accretion model.

[2] Ana Maria A. Piso and Andrew N. Youdin. "On the minimum core mass for giant planet formation at wide separations". In: *Astrophysical Journal* 786.1 (2014). ISSN: 15384357. DOI: 10.1088/0004-637X/786/1/21.

Three categories of the core accretion models.

1. Static models
   The accretion of planetesimals provides a steady luminosity that determines the structure and mass of the atmosphere.
   Limitation: Neglect the heat generated by atmospheric collapse, which can transform the core accretion instability into slower process of Kelvin-Helmholtz contraction.
2. Quasi-static models
   Include time-dependent atmospheric evolution, have 3 phases.
   a. Rapid planetesimals accretion.
   b. Atmosphere grows, cooling by KH contraction.
   c. The run-away growth of atmosphere.
3. Dynamical models
   How runaway growth ends and the final planet mass (Gap opening in disks and the transition of accretion from spherical to planar)

Some possible answers of the puzzle.

1. Late stage core formation
   The final assembly of super-Earth cores from mergers of proto-cores is delayed by gas dynamical friction[3].
2. To cool is to accret
   a. Tidally-forced turbulent diffusion[4].
   b. Tidal heating of young super-Earth atmospheres[5].
   c. High opacity atmosphere[6].
   d. Rapid recycling[7].
3. Gap opening

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[3] Eve J. Lee, Eugene Chiang, and Chris W. Ormel. "Make super-earths, not jupiters: Accreting nebular gas onto solid cores at 0.1 AU and beyond". In: *Astrophysical Journal* 797.2 (2014). arXiv: 1409.3578.

[4] Cong Yu. "The Formation of Super-Earths by Tidally Forced Turbulence". In: *The Astrophysical Journal* 850.2 (2017), p. 198. ISSN: 0004-637X. DOI: 10.3847/1538-4357/aa9849. arXiv: 1711.00594.

[5] Sivan Ginzburg and Re'em Sari. "Tidal heating of young super-Earth atmospheres". In: *Monthly Notices of the Royal Astronomical Society* 464.4 (2017), pp. 3937–3944. arXiv: 1608.03718.

[6] Eve J. Lee and Eugene Chiang. "To cool is to accrete: analytic scalings for nebular accretion of planetary atmospheres". In: *Astrophysical Journal* 811.1 (2015), p. 41. arXiv: 1508.05096.

[7] Chris W. Ormel, Ji Ming Shi, and Rolf Kuiper. "Hydrodynamics of embedded planets' first atmospheres - II. A rapid recycling of atmospheric gas". In: *Monthly Notices of the Royal Astronomical Society* 447.4 (2015), pp. 3512–3525. ISSN: 13652966. DOI: 10.1093/mnras/stu2704. arXiv: 1410.4659.

The dynamical tides can be an answer.

We choose the quasi-static model, and concentrate our attention on the phase 2. The effect of the dynamical tides serves as a kind of mechanism belong to the "to cool is to accret" scenario.
The dynamical tides can modulate the rate of cooling, thus avoiding gas giant formation.

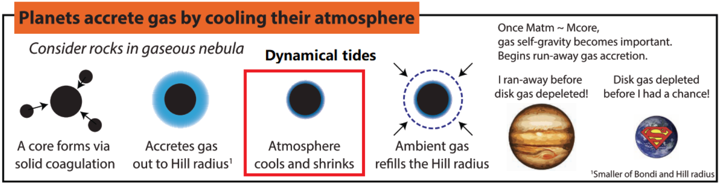


Figure 1: Credit: Eve J. Lee1, Eugene Chiang1, Chris Ormel

Model setup

The assumptions of our atmosphere models of super-Earth:

1. The atmosphere is spherically symmetric.
2. The core mass and radius is fixed.
3. Two layers: Inner zone is convective, while outer is radiative[8].
4. The dynamical wave dissipate all the energy in the outer layers, no reflection.

$$\Delta t_{old} = \frac{-\Delta E + \langle e \rangle \Delta M - P \langle V \rangle}{\langle L_{old} \rangle} \tag{1}$$

$$\langle L_{new} \rangle = \langle L_{old} \rangle - \dot{E} \tag{2}$$

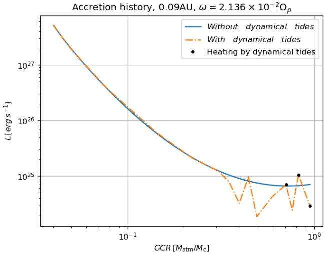
Here, $\dot{E}$ is the luminosity generated from dynamical tides.

$$\Delta t_{new} = \frac{-\Delta E + \langle e \rangle \Delta M - P \langle V \rangle}{\langle L_{new} \rangle} \tag{3}$$

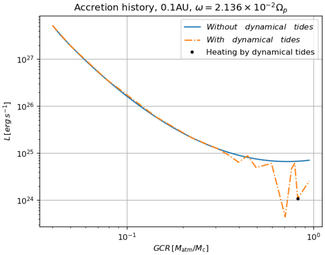
[8] Phil Arras and Lars Bildsten. "Thermal Structure and Radius Evolution of Irradiated Gas Giant Planets". In: *The Astrophysical Journal* 650.1 (2006), pp. 394–407. DOI: 10.1086/506011.

Numerical results

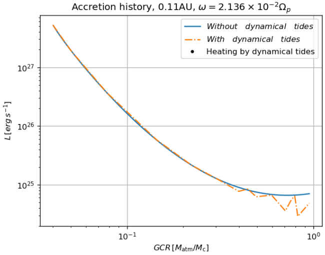
We set the tidal forcing frequency $\omega = 2.136 \times 10^{-2}\Omega_p$ as a constant. It should be noted that the spin frequency $\Omega_s = 0.5635\Omega_p$, while the orbital frequency $\Omega = 0.5742\Omega_p$, which means the orbital frequency is very close to the spin frequency. Under this condition, we find that 0.1AU is the critical orbital radius.



Accretion history, 0.09AU, $\omega = 2.136 \times 10^{-2}\Omega_p$
Without dynamical tides
With dynamical tides
Heating by dynamical tides
$L\,[erg\,s^{-1}]$
$GCR\,[M_{\rm atm}/M_{\rm c}]$

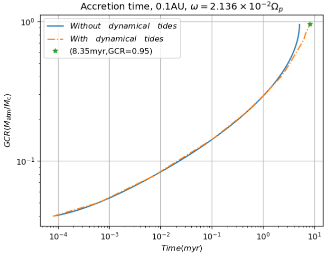


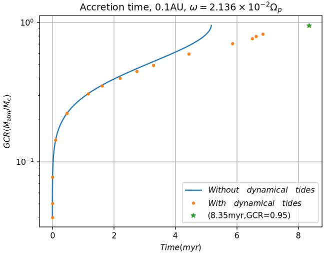
Accretion history, 0.1AU, $\omega = 2.136 \times 10^{-2}\Omega_p$
Without dynamical tides
With dynamical tides
Heating by dynamical tides
$L\,[erg\,s^{-1}]$
$GCR\,[M_{\rm atm}/M_{\rm c}]$



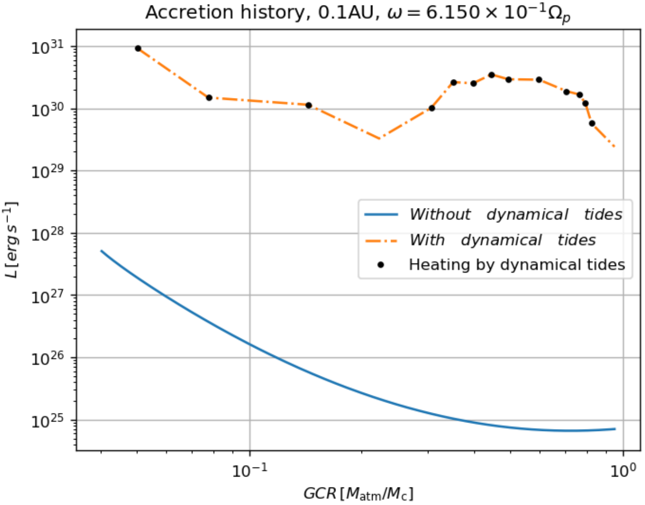
Accretion history, 0.11AU, $\omega = 2.136 \times 10^{-2}\Omega_p$
Without dynamical tides
With dynamical tides
Heating by dynamical tides
$L\,[erg\,s^{-1}]$
$GCR\,[M_{\rm atm}/M_{\rm c}]$

Numerical results





From 5.17myr to 8.35 myr.



Larger forcing frequency, the evolution history will be dominated by the tidal heating,

Numerical results

Why we choose 0.10AU: Closer means stronger dynamical tides effect..

Table 2
Average Number of Planets Per Star Per Period Bin (in Percent)

Class	Period Range (days)										
	0.8–2.0	2.0–3.4	3.4–5.9	5.9–10	10–17	17–29	29–50	50–85	85–145	145–245	245–418[a]
Giants	0.015 ±0.007	0.067 ±0.018	0.17 ±0.03	0.18 ±0.04	0.27 ±0.06	0.23 ±0.06	0.35 ±0.10	0.71 ±0.17	1.25 ±0.29	0.94 ±0.28	1.05 ±0.30
Large Neptunes	0.004 ±0.003	0.006 ±0.006	0.11 ±0.03	0.091 ±0.030	0.29 ±0.07	0.32 ±0.08	0.49 ±0.12	0.66 ±0.16	0.43 ±0.17	0.53 ±0.21	0.24 ±0.15
Small Neptunes	0.035 ±0.011	0.18 ±0.03	0.73 ±0.09	1.93 ±0.19	3.67 ±0.39	5.29 ±0.64	6.45 ±1.01	5.25 ±1.05	4.31 ±1.03	3.09 ±0.90	...
Super-Earths	0.17 ±0.03	0.74 ±0.13	1.49 ±0.23	2.90 ±0.56	4.30 ±0.73	4.49 ±1.00	5.29 ±1.48	3.66 ±1.21	6.54 ±2.20	... ...	... ...
Earths	0.18 ±0.04	0.61 ±0.15	1.72 ±0.43	2.70 ±0.60	2.70 ±0.83	2.93 ±1.05	4.08 ±1.88	3.46 ±2.81	...	...	...
Total	0.41 ±0.05	1.60 ±0.20	4.22 ±0.50	7.79 ±0.85	11.2 ±1.2	13.3 ±1.6	16.7 ±2.6	13.7 ±3.2	...	...	...

Figure 2: Table 2 of the paper[9]

0.1AU corresponds to 11.5 days, our numerical results can explain 17.9% (or more, since we don't search the upper limit of semi-major axis) of super-Earths.

[9] François Fressin et al. "The false positive rate of Kepler and the occurrence of planets". In: *Astrophysical Journal* 766.2 (2013). ISSN: 15384357. DOI: 10.1088/0004-637X/766/2/81. arXiv: 1301.0842.

THANKS