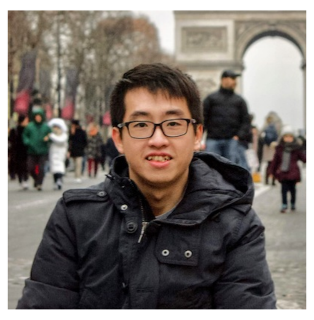
Sequential Giant Planet Formation in a Substructured Disk



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Introduction

- ALMA has revealed that rings are common in protoplanetary disks
  - These rings were shown to be consistent with models of dust trapping in gas pressure maxima [6, 13, 14]
- In a previous paper [9], we have shown that such pressure bumps aid rapid formation of planetary cores by solving several problems at once:
  - they enhance the local dust-to-gas ratio, thereby trigger planetesimal formation
  - the accumulation of dust accelerates the growth of cores via pebble accretion
  - they prevent migration, retaining the massive cores.
  - Massive cores can form at $\sim$ 100 au in 0.5 Myr as shown in [9]

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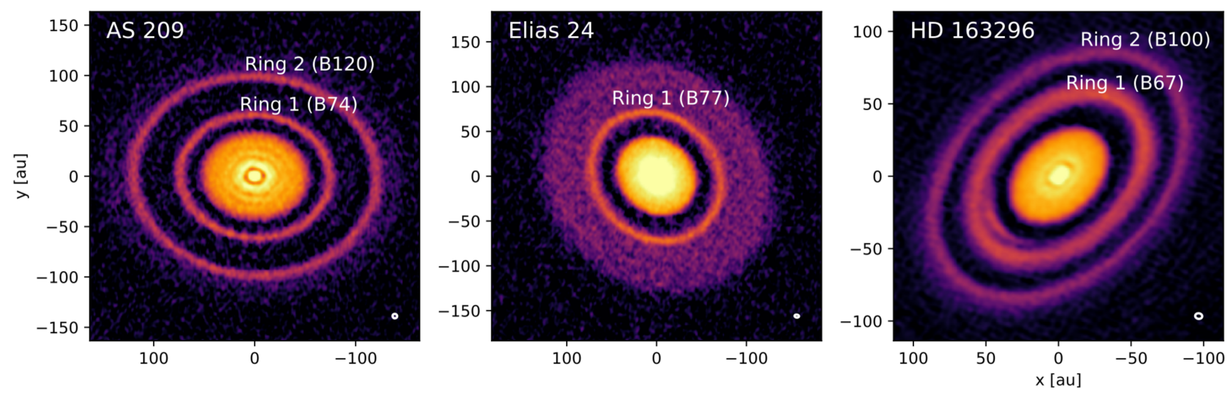
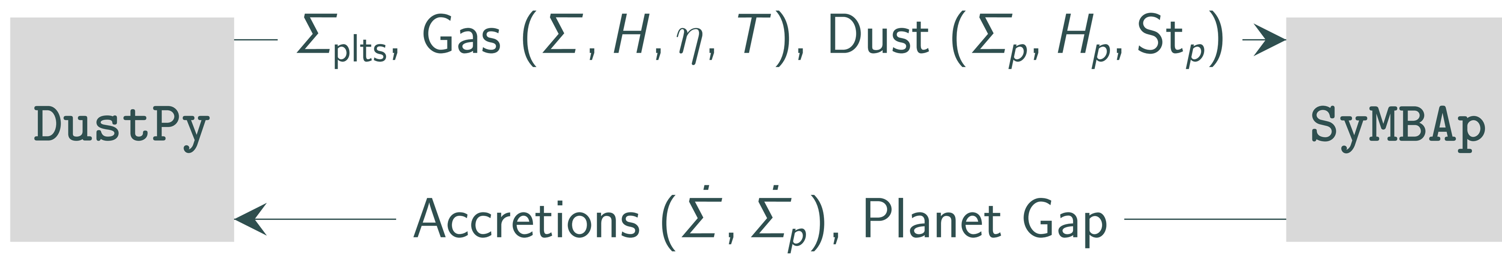
- Continuing from the previous paper, we added gas accretion and gap opening



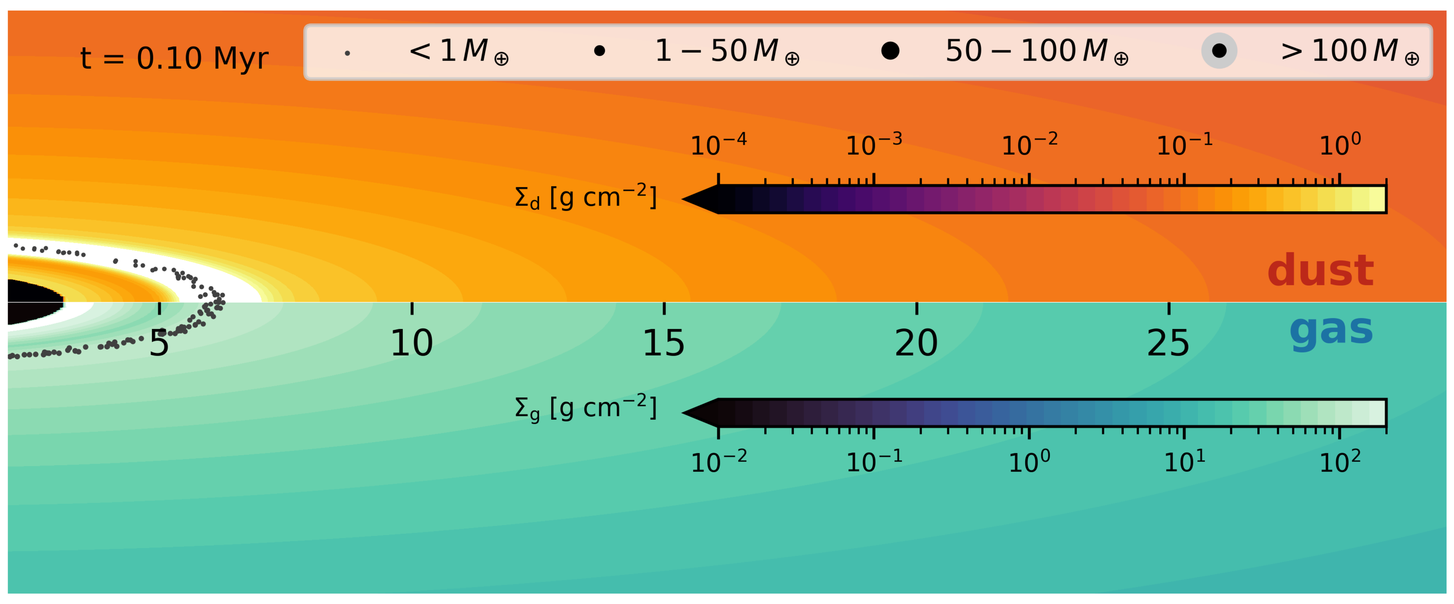
Method

We model the formation and evolution of planetesimals in an axisymmetric pressure bump

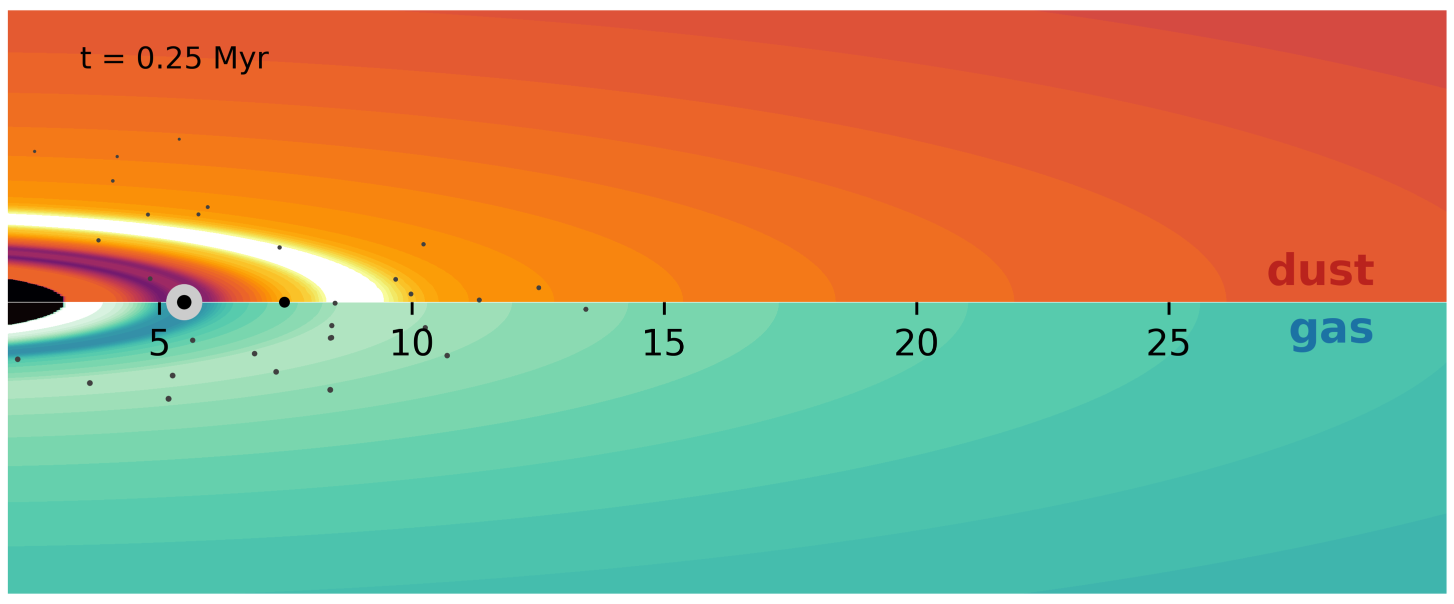
- The dust and gas evolution code DustPy [12] coupled to the parallelized symplectic direct N-body code SyMBAp [in prep.]
- Disk: $M_* = M_\odot$, $M_{disk} = 0.05 M_\odot$, $r_c = 100$ au, $Z = 1\%$, $\alpha = 10^{-3}$, ISM-sized dust
- Prescribed Gaussian gap [6] at 5 au without pre-existing planet
- The IMF of planetesimals follows [7] with the small-scale turbulence $\delta = 10^{-5}$
- We include pebble accretion [10, 11], gas drag [1], e & i-damping, Type-I migration [8]
- Added to previous work [9]: gas accretion [4, 2] (const. $\kappa = 0.05$ cm^{2}g^{-1}), planetary gap opening [5]



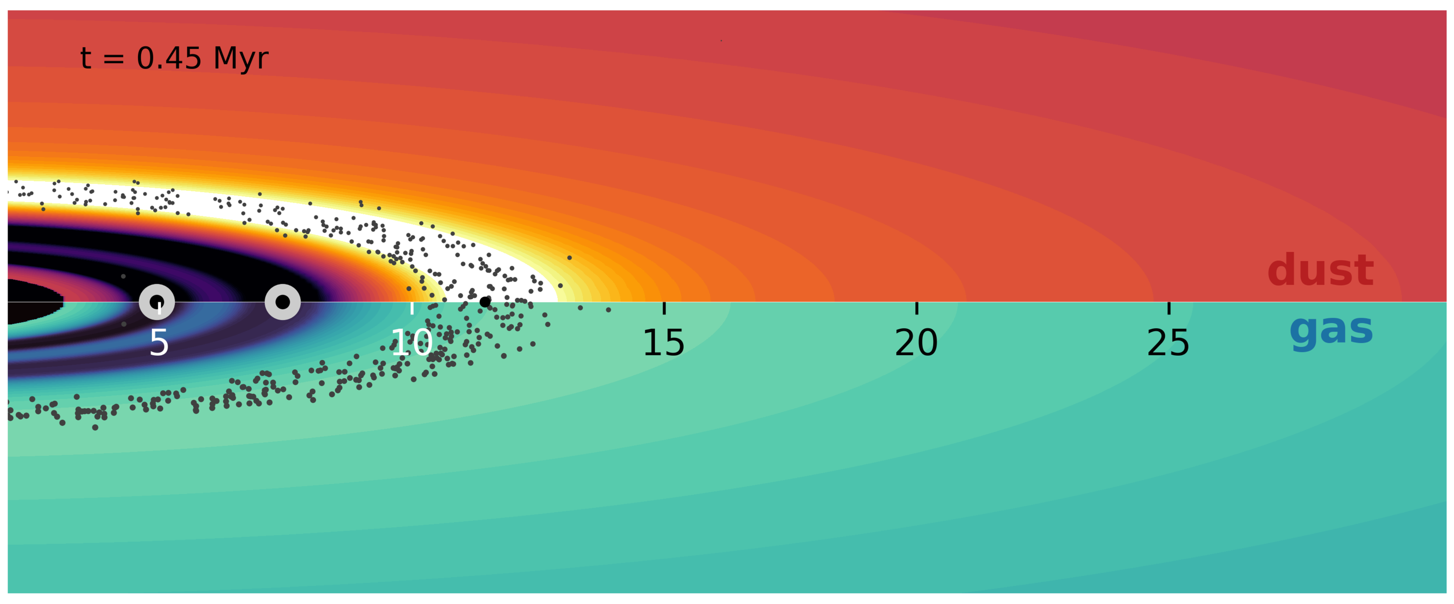
Results - Sequential planet formation



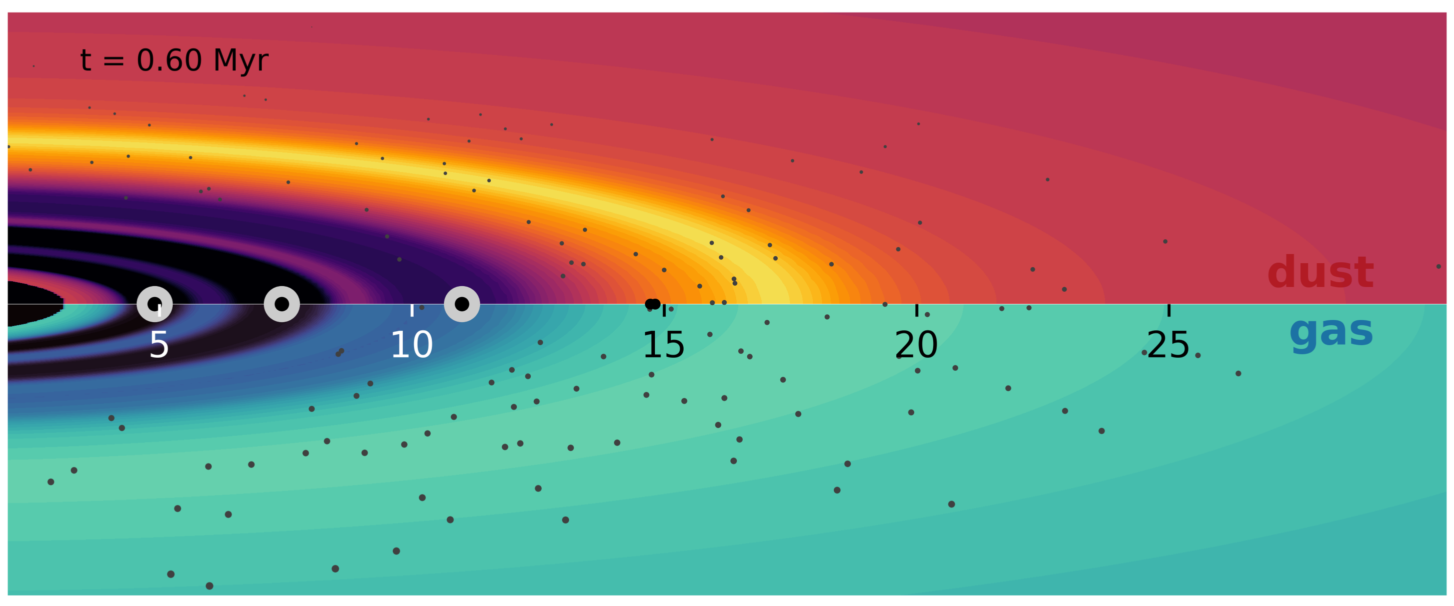
- Dust trapped at pressure bump and triggers planetesimal formation



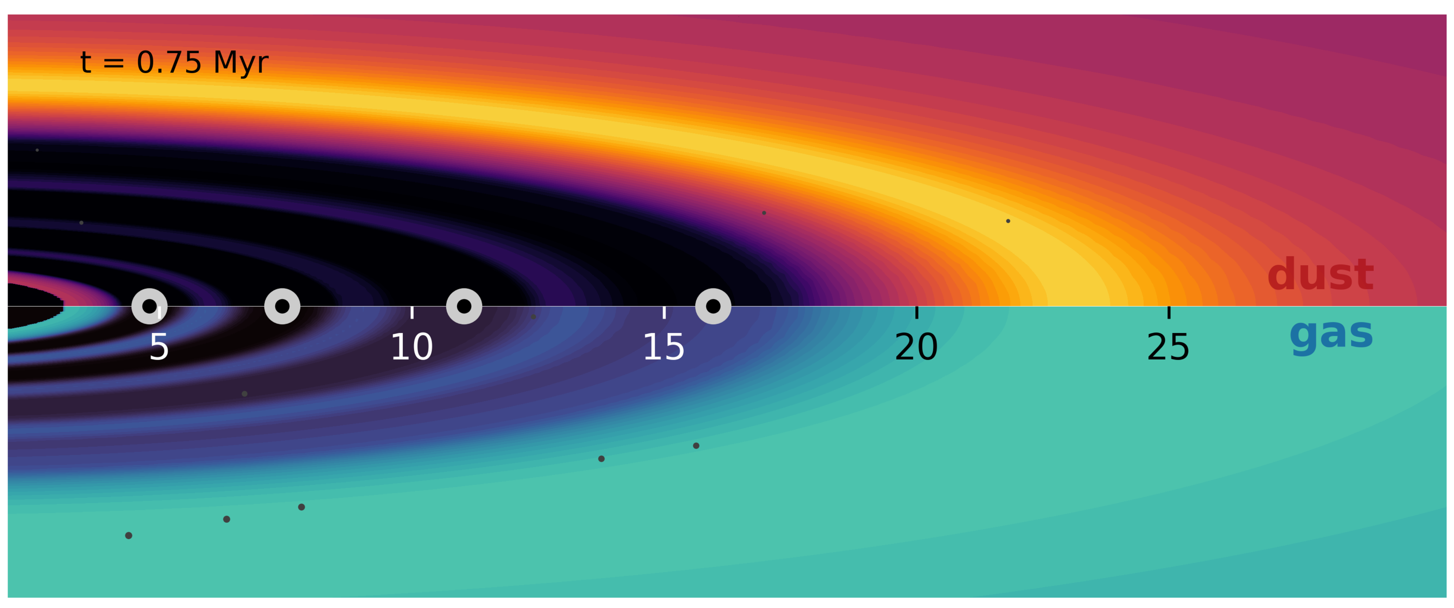
- Multiple planetary cores are formed at the bump and retained at wide orbit



- Cores grow by gas accretion and open gap
- Pressure bump forms at a new location & traps dust



- Next generation of planets formed

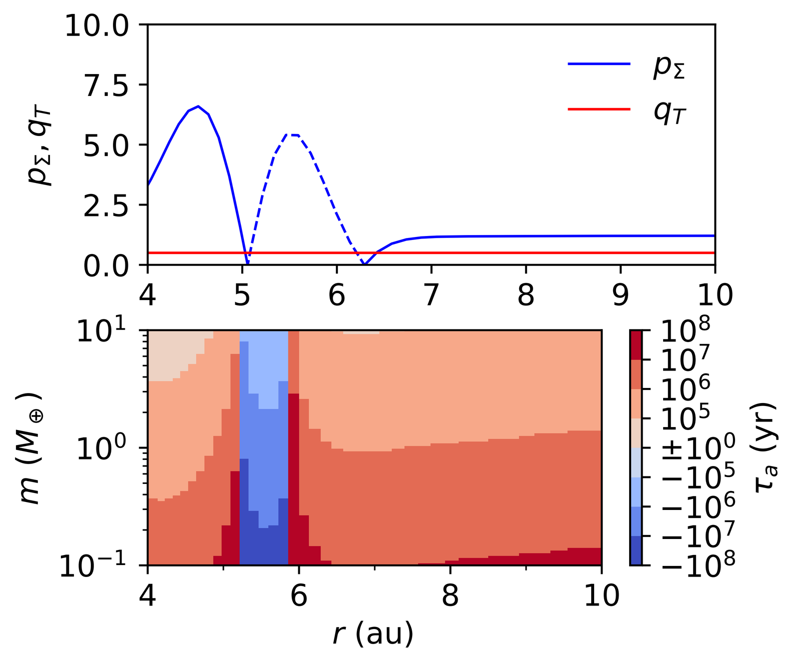


- Two generations of giant planets formed in 0.75 Myr

Discussions

Pressure bump

- Enhanced pebble flux (10 – 100 times of typical value) for efficient growth
- Migration direction changes & traps planet



Slopes of the disk surface density and temperature (top). Migration timescale τ_a near pressure bump (bottom).

Architecture of planetary system

- Final mass set by depth of planetary gap
- Ice giant missing
  - Disk dispersal before runaway gas accretion could stop the growth
  - Opacity of gas envelope likely depends on local disk condition [3]
- Long-term instability likely occurs within Myr timescale
- The Kuiper Belt Objects can form from final generation of planetesimals
  - Small objects ($\lesssim 0.1 M_\oplus$) are formed at $\sim 30 - 50$ au
  - Outermost ice giant stirs KBOs into eccentric orbits and halts pebble accretion
  - The observed eccentricity of the KBOs ($\lesssim 0.1$) is enough to prevent significant growth by pebble accretion

Conclusions

- In pressure bumps, growth from ISM-sized dust to giant planet takes only $\sim$0.25 Myr at 5 au and 0.5 Myr at 100 au up to massive cores
- Planetary cores accrete gas near the pressure bump and remain at wide orbits
- Dust trapped at the new pressure bump formed by gap opening can trigger a new generation of planetesimal formation
- Further investigation on envelope opacity required to form ice giants

References

[1] I. Adachi, C. Hayashi, and K. Nakazawa. *Progress of Theoretical Physics*, 56(6):1756–1771, 1976.

[2] B. Bitsch, M. Lambrechts, and A. Johansen. *A&A*, 582:A112, 2015.

[3] M. G. Brouwers, C. W. Ormel, A. Bonsor, and A. Vazan. *A&A*, 653:A103, 2021.

[4] J. Chambers. *ApJ*, 914(2):102, jun 2021.

[5] P. C. Duffell. *ApJ*, 889(1):16, jan 2020.

[6] C. P. Dullemond, T. Birnstiel, J. Huang, N. T. Kurtovic, S. M. Andrews, V. V. Guzmán, L. M. Pérez, A. Isella, Z. Zhu, M. Benisty, D. J. Wilner, X.-N. Bai, J. M. Carpenter, S. Zhang, and L. Ricci. *ApJ*, 869(2):L46, 2018.

[7] K. Gerbig and R. Li. *arXiv e-prints*, page arXiv:2301.13297, Jan. 2023.

[8] S. Ida, T. Muto, S. Matsumura, and R. Brasser. *MNRAS*, 494(4):5666–5674, 2020.

[9] T. C. H. Lau, J. Drazkowska, S. M. Stammler, T. Birnstiel, and C. P. Dullemond. *A&A*, 668:A170, 2022.

[10] B. Liu and C. W. Ormel. *A&A*, 615:A138, 2018.

[11] C. W. Ormel and B. Liu. *A&A*, 615:A178, 2018.

[12] S. M. Stammler and T. Birnstiel. *ApJ*, 935(1):35, aug 2022.

[13] R. Teague, J. Bae, E. A. Bergin, T. Birnstiel, and D. Foreman-Mackey. *ApJ*, 860(1):L12, 2018.

[14] R. Teague, J. Bae, T. Birnstiel, and E. A. Bergin. *ApJ*, 868(2):113, 2018.

Acknowledgements

We acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 714769 and funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under grant 325594231 and Germany's Excellence Strategy – EXC-2094 – 390783311 and EXC 2181/1 – 390900948 (the Heidelberg STRUCTURES Excellence Cluster). J.D. was funded by the European Union under the European Union's Horizon Europe Research & Innovation Programme 101040037 (PLANETOIDS).