Pebble drift and planetesimal formation in protoplanetary disks with planets

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Abstract

Recent observations with ALMA have revealed that most protoplanetary disks have dark and bright annular rings in their emission at mm wavelengths (Andrews et al. 2018). If the dark rings are carved by growing protoplanets (Pinilla et al. 2012), then the regions just outside the dark rings should correspond to locations where there is a local pressure maxima. At such locations drifting pebbles become trapped, resulting in an increased solid-to-gas ratio which if it becomes high enough, leads to planetesimal formation via the streaming instability (Yang et al. 2017). We study how efficient this planetesimal formation mechanism is and find that it is capable of producing over a hundred Earth masses of planetesimals within the lifetime of the disk. The main pathway for crossing the growth barrier from pebbles to planetesimals in protoplanetary disks may thus be via streaming instabilities in planet-induced pressure bumps.

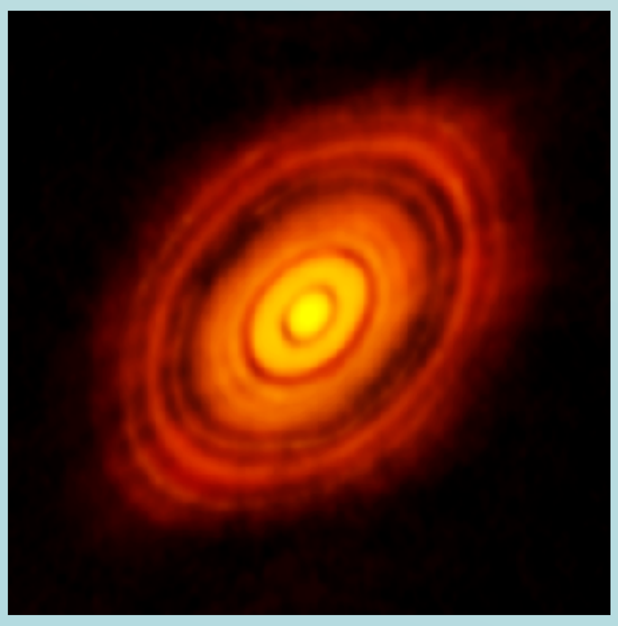
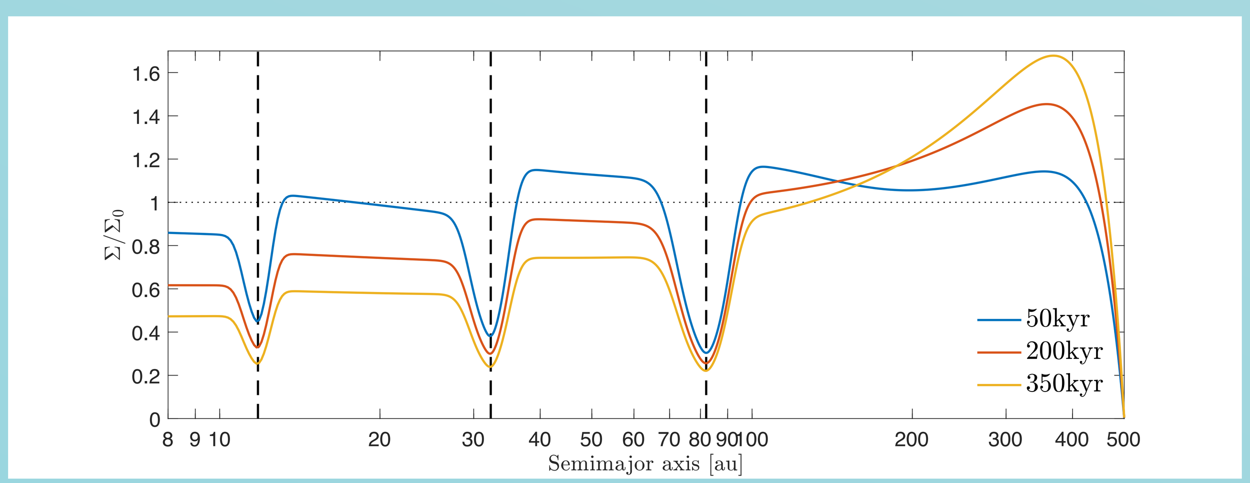


Image of the protoplanetary disk surrounding the young star HL Tauri. Credit: ALMA (ESO/NAOJ/NRAO)

Disk structure

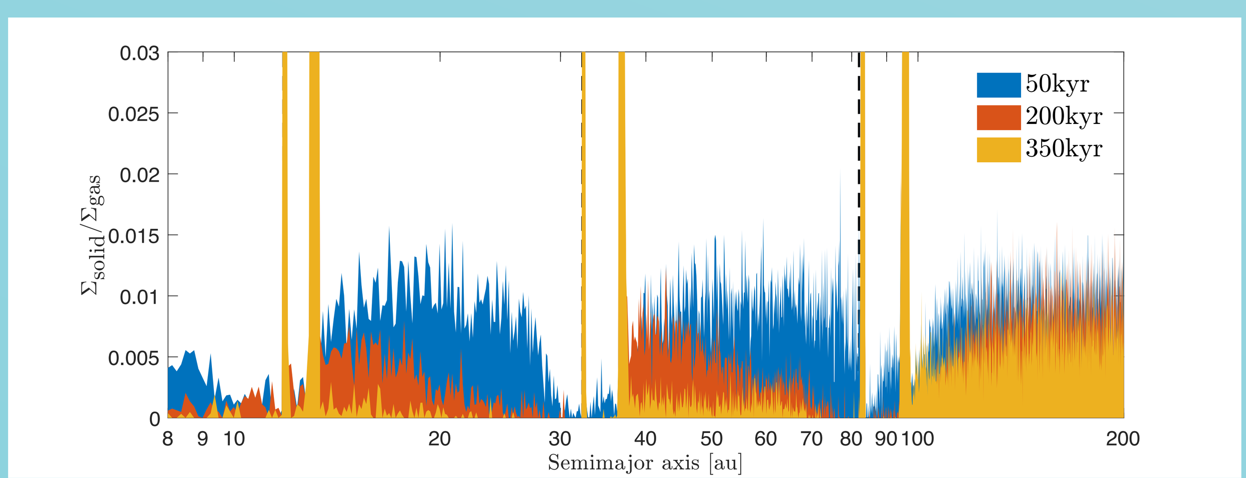
We use the 1D viscous evolution model of Lin & Papaloizou (1986). Gap-opening planets are inserted at locations corresponding to the three major gaps in the disk around HL Tauri.



Evolution of the normalised gas surface density across the protoplanetary disk for the nominal model.

Dust evolution

Collisions between dust particles results in either sticking, bouncing or fragmentation (Güttler et al. 2010). These processes results in the formation of mm-sized pebbles, which drift fast towards the star, rapidly clearing the region in between the planets of pebbles. Once the pebbles encounter a pressure maxima, they become trapped, resulting in an enhanced solid-to-gas ratio.



Evolution of the solid-to-gas surface density across the protoplanetary disk for the nominal model.

Planetesimal formation

If the solid-to-gas ratio in the pressure maximas become higher than a certain critical value, the streaming instability is triggered and planetesimals are formed (Yang et al. 2017). This process is very dependent on the pressure gradient in the disk: the lower the pressure gradient, the easier it is to form planetesimals (Bai & Stone 2010). This results in that planetesimals almost exclusively forms in narrow rings outside the planetary gaps, at the locations of the local pressure maxima.

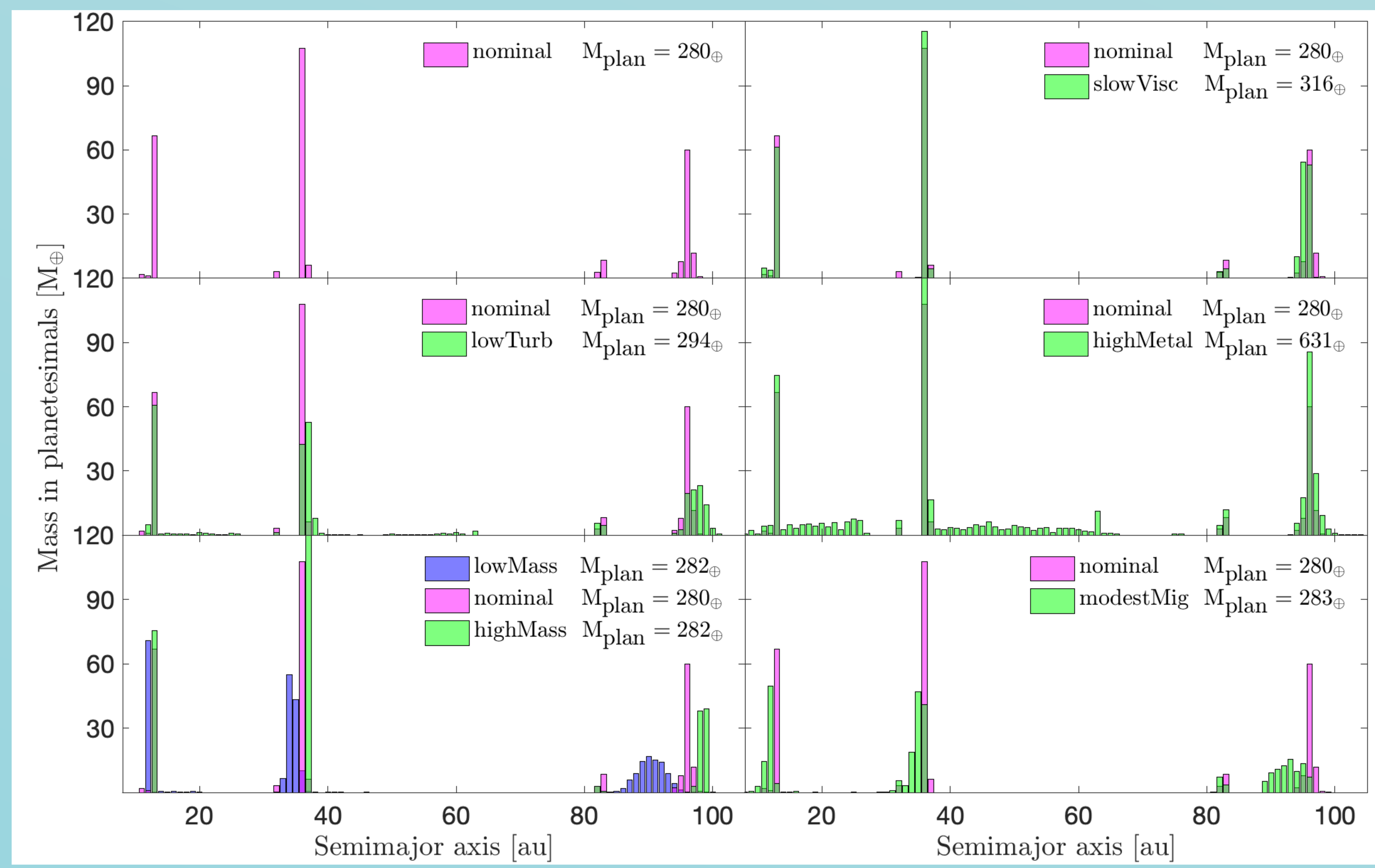
Parameter study

To explore how different parameters affect the distribution of particles and the planetesimal formation efficiency, we conduct a parameter study in which we vary the efficiency of viscous transport, the level of turbulence, the disk metallicity, the planetary mass, and weather or not the planets migrate.

Run	α_{visc}	α_{turb}	Z	M_P (M_{iso})	V_P (ms^{-1})
#1 nominal	10^{-2}	10^{-3}	0.01	2	0
#2 slowVis	10^{-3}	10^{-3}	0.01	2	0
#3 lowTurb	10^{-2}	10^{-4}	0.01	2	0
#4 highMetal	10^{-2}	10^{-3}	0.02	2	0
#5 lowMass	10^{-2}	10^{-3}	0.01	1	0
#6 highMass	10^{-2}	10^{-3}	0.01	3	0
#7 migration	10^{-2}	10^{-3}	0.01	2	0.03

The amount of mass in planetesimals vary very little between the simulations, with the exception of #4 where the initial solid-to-gas ratio was doubled. This is because the critical solid-to-gas ratio becomes very low at the pressure maxima, resulting in that essentially all trapped pebbles are turned into planetesimals.

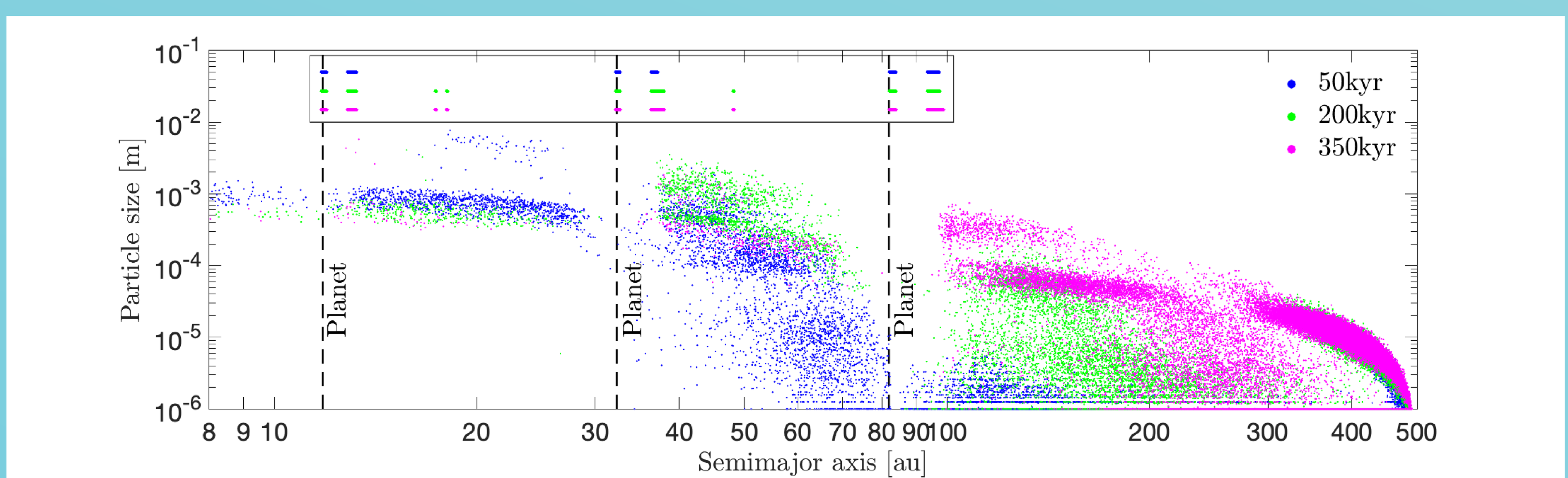
The distribution of planetesimals within the disc vary more between the runs, as can be seen in the histogram to the right.



Histograms showing the final mass distribution of planetesimals for different simulations in the parameter study.

Results & conclusions

- Planets above the pebble isolation mass catch drifting pebbles very efficiently
- These pebbles are converted to planetesimals
- This mechanism can produce over a hundred Earth masses of planetesimals within 1Myr
- Planetesimal formation in pressure bumps might be the dominant mechanism for converting dust into planetesimals
- Pebbles of millimeter sizes drift out of regions between planets in ~300kyr
- This is inconsistent with most observations
- Can reconcile with observations if:
  - Pebbles are 100 micron and drift slowly
  - Dust is transported across planetary gaps by some unknown mechanism
  - Dark rings are not caused by planets after all



Size distribution of particles in the protoplanetary disk at different times during disk evolution for the nominal model. The horizontal coloured lines in the box at the top of the plot shows at what locations planetesimals have formed in the disk.

References

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