How did super-Earths acquire their atmospheres?

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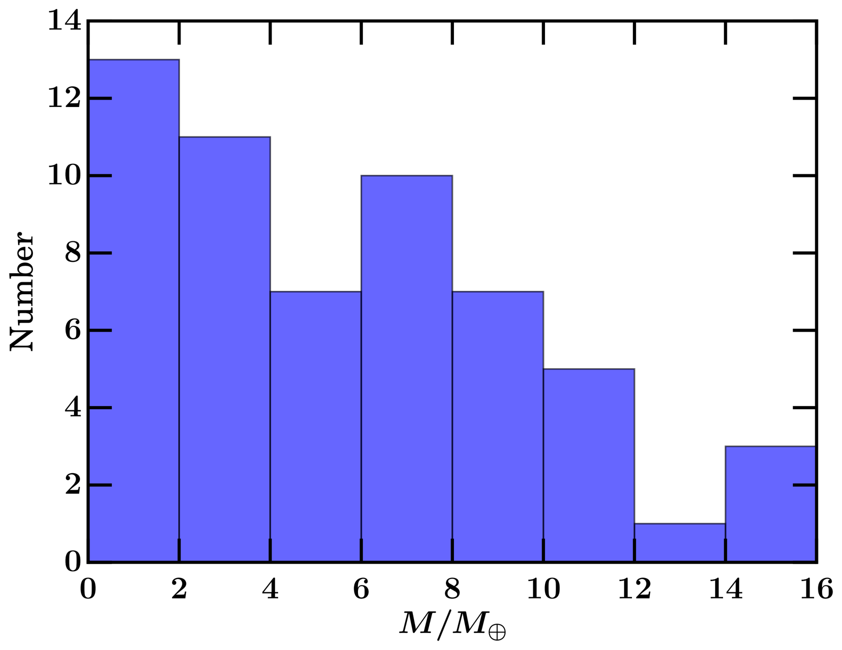
Super-Earths can be as massive as 10 $M_\oplus$

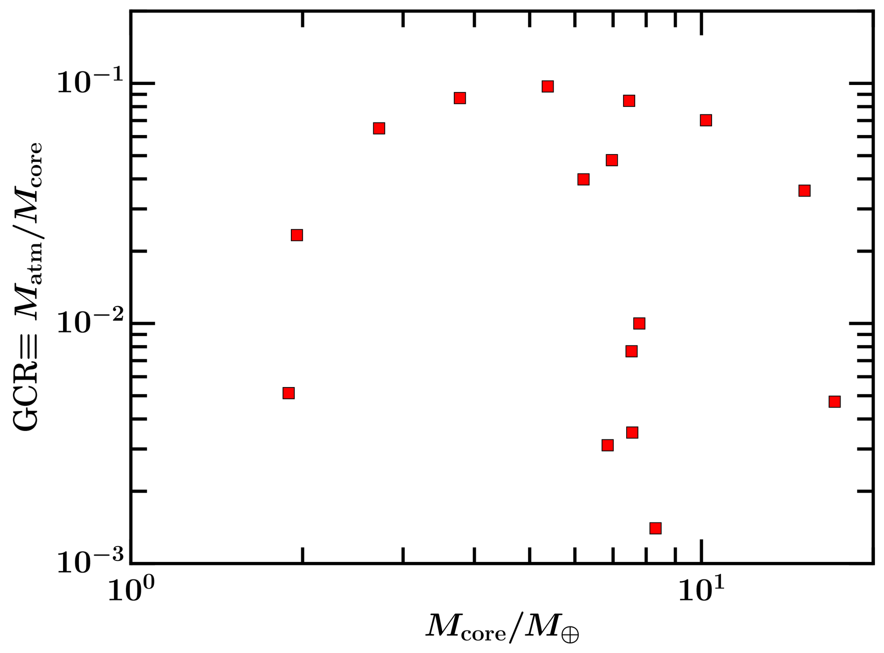
Mass histogram of planets with $R < 4R_\oplus$



Sub-Neptune planets have a mass range of ~0.1 $M_\oplus$ to ~16 $M_\oplus$. Planets of mass ~10 $M_\oplus$ are expected to become gas giants.

(Weiss & Marcy 2014)

with a few %wt atmosphere



Atmospheric fraction as a function of mass for planets with $R < 4R_\oplus$

Mini-Neptunes and super-Earths have <10% H/He atmosphere.

(Lopez & Fortney 2014)

Why just a few % atmosphere? Can this be explained from primordial gas accretion?

Proto-cores need to have high eccentricity to cross orbits and merge.

Viscous stirring **pumps** eccentricity
Gas dynamical friction **damps** eccentricity

Gas needs to deplete to allow orbit crossing.

Planets accrete gas by cooling their atmosphere

Consider rocks in gaseous nebula

Once Matm ~ Mcore, gas self-gravity becomes important. Begins run-away gas accretion.

I ran-away before disk gas depeleted!

Disk gas depleted before I had a chance!

[1]Smaller of Bondi and Hill radius

Two scenarios of gas acquisition

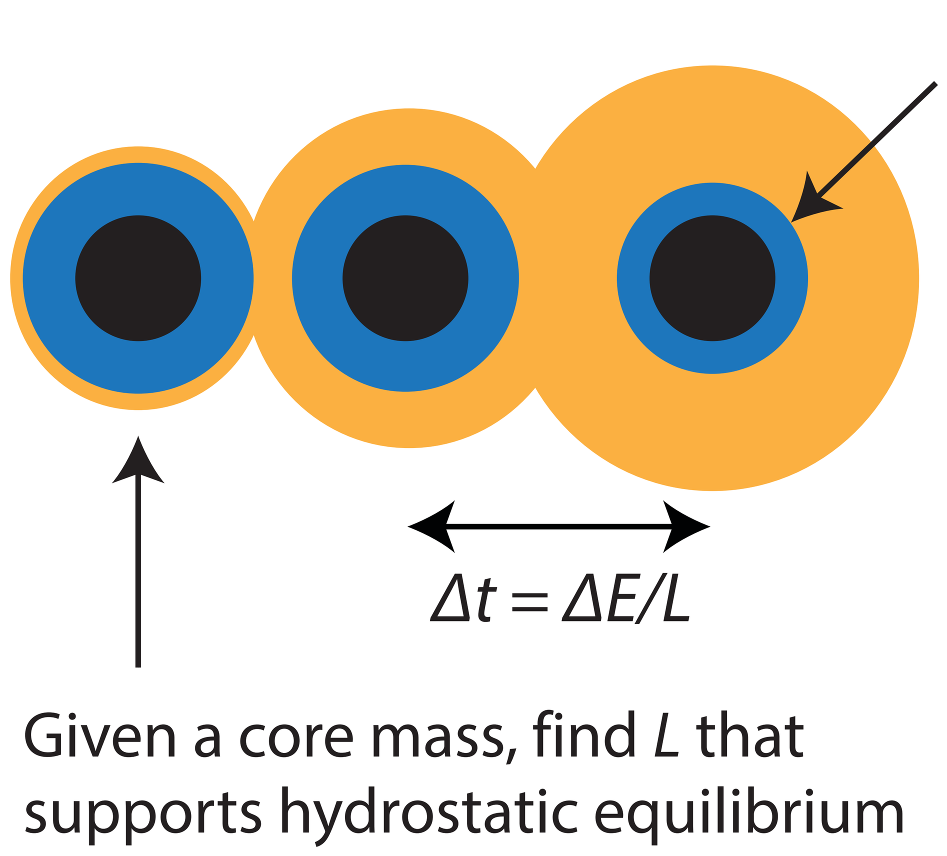
A. Cores form before disk gas depletes

- Cores accrete gas from full nebula
- Avoid gas giant by limiting the rate of cooling

B. Cores form after disk gas depletes

- Cores accrete gas from depleted nebula
- Avoid gas giant by limiting the mass reservoir

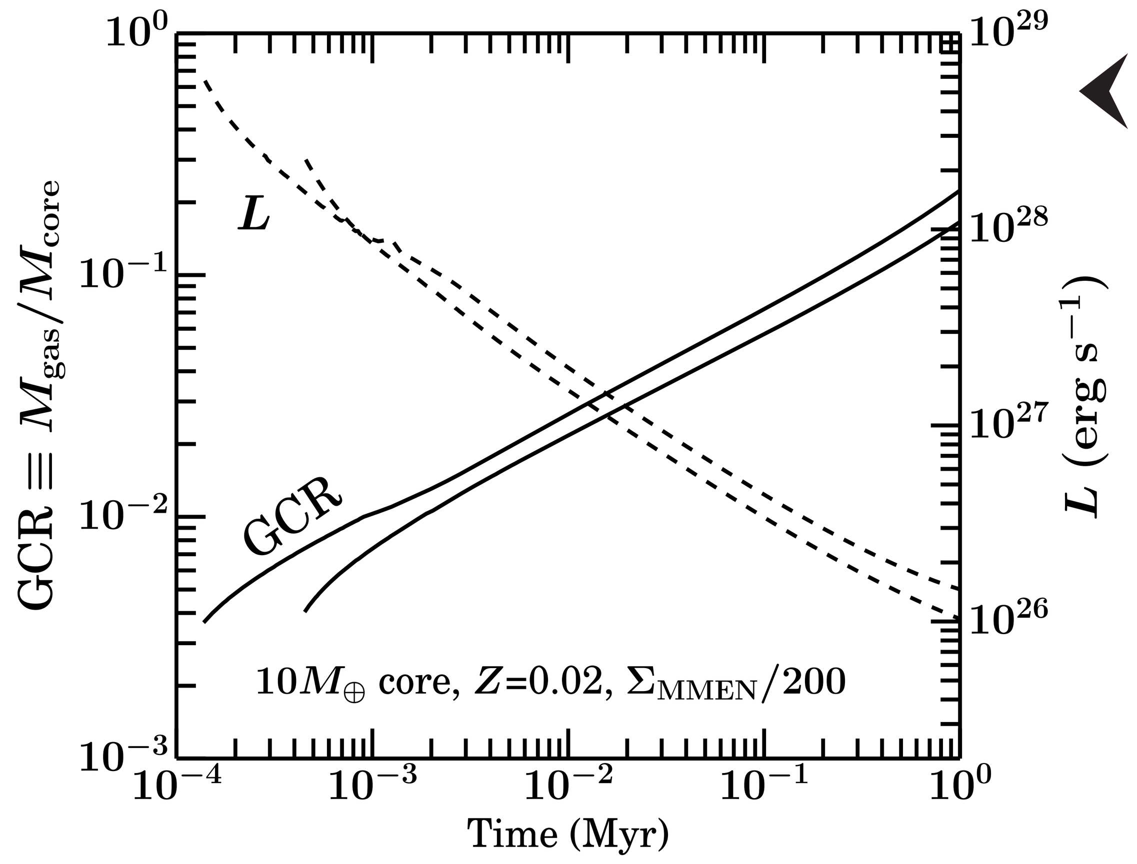
Model set-up



- Ideal gas EOS with H_2, HI, HII, He atoms, metallic atoms
- Opacity with and without grains (Ferguson+2005)

Caveat: no heating

Gas accretion in depleted nebula gives <20% atmosphere

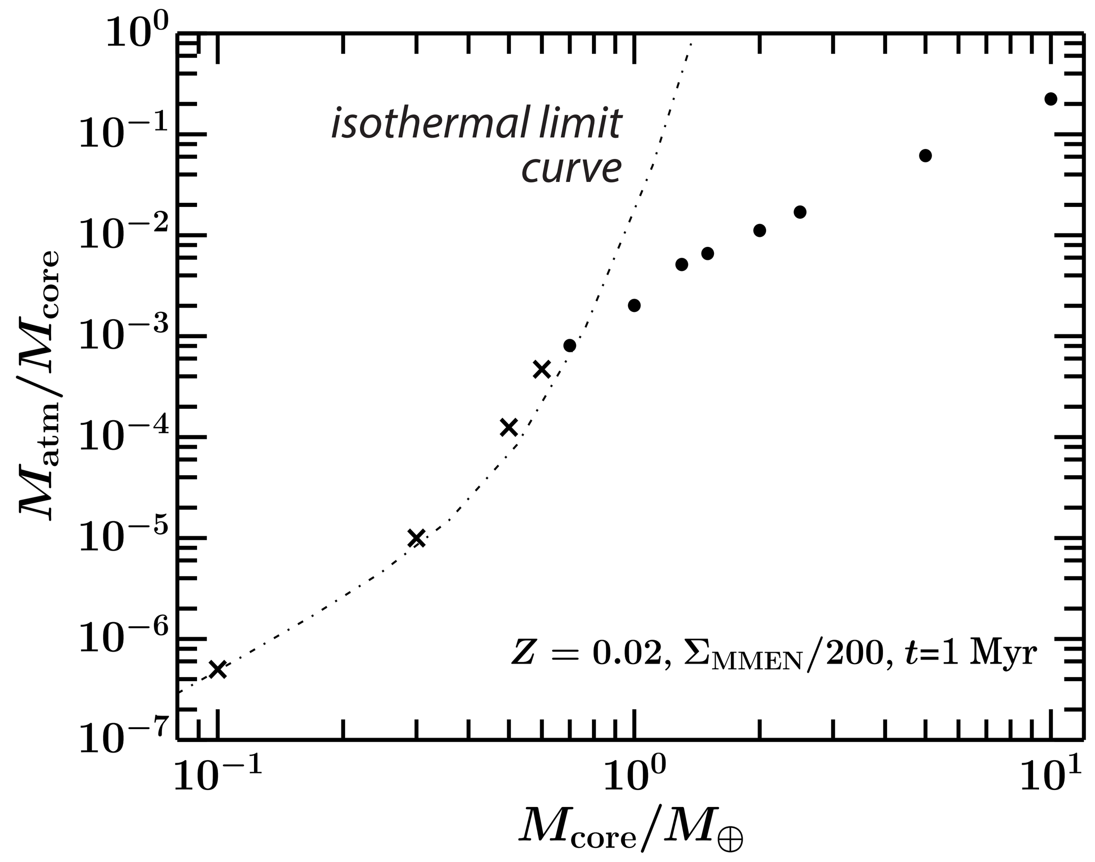


Evolution of atmospheric mass fraction and luminosity.

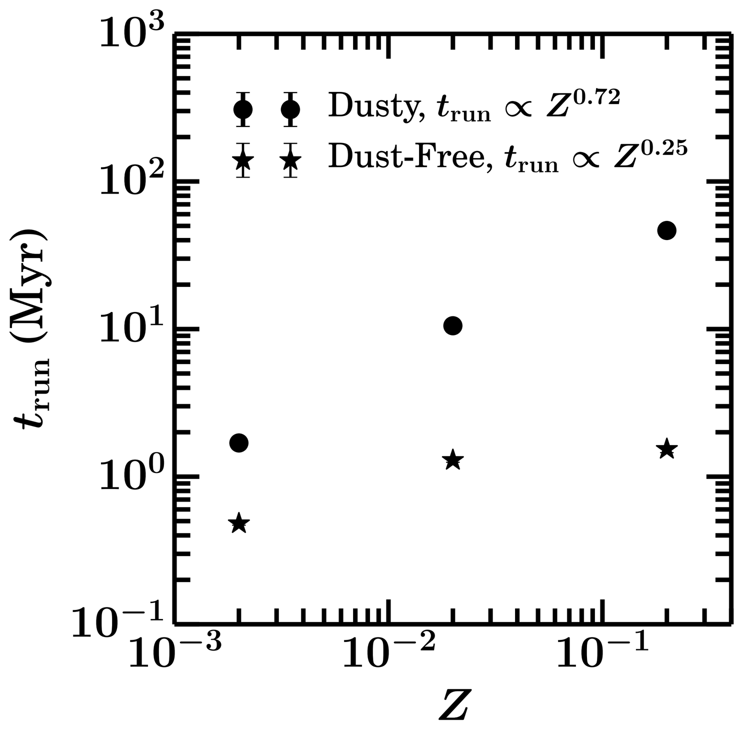
Largest core can accrete 10--20% atmosphere.

Atmospheric fraction at 1 Myr as a function of core mass

Sub-Earth masses cannot accrete more than 0.1%.



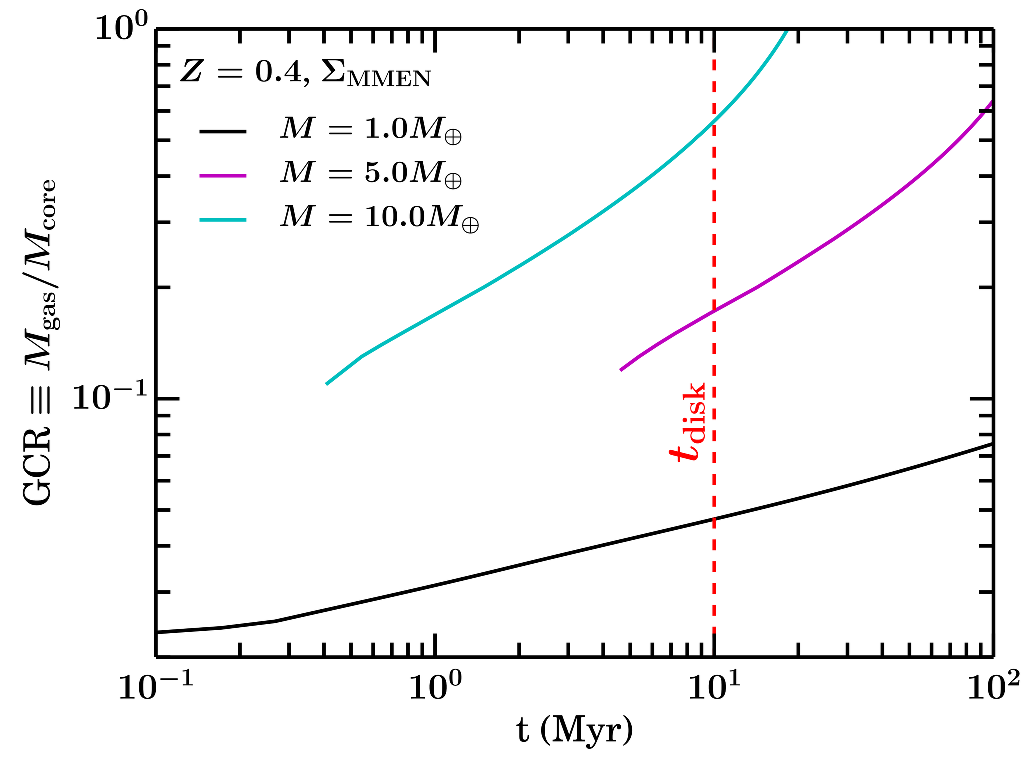
Gas accretion in full nebula requires high metallicity



Time to run-away gas accretion as a function of metallicity

Higher metallicity gives higher opacity, making the atmosphere harder to cool.

Evaporation of dust grains pushes RCB deeper into the atmosphere.



Evolution of atmospheric mass fraction for different core masses

Even an Earth mass core accretes ~4% atmosphere.

Largest core mass barely avoids becoming a gas giant

Primordial gas accretion CAN reproduce super-Earth atmospheres!

References

- Ferguson, J. W., Alexander, D. R., et al. 2005, ApJ, 623, 585
- Fressin, F., Torres, G., Charbonneau, D., et al. 2013, ApJ, 766, 81
- Lopez, E. D., & Fortney, J. J. 2014, ApJ, 792, 1
- Weiss, L. M., & Marcy, G. W. 2014, ApJL, 783, L6