How are planetary atmospheres shaped by early-on planetary dynamics?

*Focus on Uranus and Neptune*

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Gas giants

- ~100-300 $M_{\text{Earth}}$ of gas (>90%)
- ~10-20 $M_{\text{Earth}}$ core

Ice giants

- ~2 $M_{\text{Earth}}$ gas (~10%)
- ~15 $M_{\text{Earth}}$ core

“$M_{\text{crit}}$” ~ 10 $M_{\text{Earth}}$

Standard accretion scenario:

Runaway gas accretion after $M_{\text{gas}}$ ~ $M_{\text{core}}$ in “full” gas disk

Gas disk dissipated before runaway could occur
Standard core accretion scenario: phase 1

$\Delta r \sim 5R_H$

Pollack et al. 1996
Standard core accretion scenario: phase 1

Phase 1

Phase 2

Phase 3

Ice giant $t_{\text{disk}}$

Gas giant $t_{\text{disk}}$
Standard core accretion scenario: phase 1

Phase 1

Phase 2

Phase 3

Ice giant $t_{\text{disk}}$

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Phase 1

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Phase 3

Ice giant $t_{\text{disk}}$

Gas giant $t_{\text{disk}}$
Standard core accretion scenario: phase 1

$M_{\text{core}} \sim M_{\text{iso}}$
Phase 2: concurrent accretion of solids and gas
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Uranus and Neptune stop when $M_{\text{gas}} \sim 0.1M_{\text{core}}$: gas disk dissipates before end of Phase 2
Phase 2: concurrent accretion of solids and gas
Phase 3: Runaway gas accretion by nucleated instability

$M_{\text{gas}} \sim M_{\text{core}}$

"$M_{\text{crit}}" \sim 10 \ M_{\text{Earth}}$

Phase 1

Phase 2

Ice giant $t_{\text{disk}}$

Phase 3

Gas giant $t_{\text{disk}}$
Too long of a Phase 2 (> disk lifetime) results in an ice giant:

\[ \sim 10\% \text{ atmosphere} \]

Reaching \( M_{\text{crit}} \) (Phase 3) in a full gas disk results in a gas giant:

\[ >90\% \text{ atmosphere} \]
Pebble accretion makes this scenario newly problematic
Pebbles are observed in the outer regions of disks

Figure scaled from Andrews et al. (2009) by Mickey Rosenthal

0.1-1 mm
feeding zone replenished with infalling pebbles

Pebbles are accreted quickly: $10^5$ years to double $12 \ M_{\text{Earth}}$ core

$M_{\text{core}} \sim M_{\text{iso}}$

Phase 1

Phase 2

Ice giant $t_{\text{disk}}$

Phase 3

Gas giant $t_{\text{disk}}$
Problem with standard scenario: 12 $M_{\text{Earth}}$ core doubles at 20 AU within $10^5$ years via PA

runaway gas accretion, no Phase 2
Too long of a Phase 2 (> disk lifetime) results in an ice giant:

\[ \sim 10\% \text{ atmosphere} \]

Reaching \( M_{\text{crit}} \) (Phase 3) in a full gas disk results in a gas giant:

\[ > 90\% \text{ atmosphere} \]

Can we stall core growth in a different way?
1. There is no radial drift of pebbles into the feeding zone

2. The supply of pebbles is cut off in the outer disk
3: Can accretion heating keep the cores sub-critical? No: the cores surpass current core masses.

To accrete, gas must cool and contract.

Heating by planetesimal accretion can slow down contraction, slowing the buildup of gas.

\[ L \sim -P \frac{dV}{dt} + \frac{GM_P}{R} \left( \frac{dM_{\text{gas}}}{dt} + \frac{dM_s}{dt} \right) \]
4. Pebble isolation limits the core growth to a sub-critical mass.

- $M_{\text{iso,peb}} \sim 27M_{\text{Earth}} (a/20 \text{ AU})^{3/4}$

*for $\sim 15 \ M_{\text{Earth}}$ to be sub-critical, the grain opacity must be higher than expected.
Preferred scenario:
Cores stay small until the very end.
Gas accretion happens in a disk depleted enough to avoid runaway, but before disk fully dissipates.
How depleted does the disk have to be to result in an intermediate-sized atmosphere?

\[ M_{\text{iso,g}} = 2\pi a \Delta r \Sigma_g(a), \text{ where } \Delta r \text{ is the width of the planetary feeding zone (typically, } \sim 5R_H) \]

\[ M_{\text{iso,g}} = M_{\text{atm}} \]

\[ f^* = 10^{-2} \]

(*depletion fraction)
f* = 10^{-2} of the initial mass

Once you have a disk that depleted, you don’t keep it very long.

\[ t_{\text{disp}} \sim 10^4 - 10^5 \text{ yr} \]
Uranus and Neptune Formation: Fine Tuned?

Gas accretion onset:
Late enough to avoid runaway, but before disk fully dissipates

Both planets have a short timeframe to finish core growth and accrete ~10% by mass atmospheres

Gas disk depleted to ~0.01 of original value

Full gas disk

Gas disk fully dissipated

(~ $10^4$-$10^5$ yr timescale for gas to fully dissipate)

Main problem for this solution: timescale to dissipate is much less than the lifetime of the disk
Key idea: disk dynamical instability coincides with start of bulk of gas accretion

For full disk: $\Sigma_{\text{solids}} \sim 0.01\Sigma_{\text{gas}}$

Start of bulk of gas accretion: $\Sigma_{\text{gas}} \sim 0.01\Sigma_{\text{gas,full disk}}$

$\rightarrow \Sigma_{\text{solids}} \sim \Sigma_{\text{gas}}$

$\rightarrow$ known factor for dynamical instability

$\rightarrow$ dynamical instability triggers this late stage of growth: not a coincidence that $\Sigma_{\text{solids}} \sim \Sigma_{\text{gas}}$ at the onset of gas accretion
Proposed Scenario: how did the dynamical instability trigger late stage of growth?

- Growth starts near Jupiter and Saturn
- $M_{\text{core}} < M_{\text{crit}}$
- Full gas disk damps orbit to circular
Proposed Solution

- $\Sigma_{\text{gas}} = \Sigma_{\text{solids}}$ : dynamical instability
- Jupiter and Saturn scatter ice giants outwards
Proposed Solution

- Ice giants circularize as they accrete pebbles at new location
- $\sim 10\%$ atmospheres are accreted from the remaining gas
- $M_{\text{core}} > M_{\text{crit}}$, but the supply of gas is limited $\rightarrow$ no runaway
Final Core Growth

• Cores of Uranus and Neptune: last doubling timescale is $\sim 10^5$ years (using pebble accretion model - gas-assisted growth)

• Once at their present-day orbits, cores finish their growth and accrete remaining gas from disk
Summary: 3 scenarios

1. The standard 3-phase scenario is possible if the core growth is limited to the pebble isolation mass, and opacities are high enough that \( M_{\text{iso,peb}} < M_{\text{crit}} \).

2. Planetesimal accretion cannot keep the core sub-critical, it makes cores too big.

3. In our preferred scenario, the ice giants finish their growth at the end of the disk lifetime. Gas depletion leads to a late stage dynamical instability, which triggers the final stage of growth.
Conclusion

Pebble accretion makes the ice giants’ final growth too fast & a solution is needed for this problem.

Early-on dynamics could have implications for current planet composition.

Gas giants may play key role in forming intermediate-size atmospheres in the outer disk.