Critical core mass and the role of H_2O condensation in enriched protoplanets

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Abstract

During the formation of a planet, once the core reaches a lunar mass, it can start to bind some gas from the protoplanetary disk. The planetesimals that are accreted from this stage on, undergo thermal ablation and physical disruption when crossing the atmosphere. Thus, the primordial H-He atmosphere gets enriched in volatiles and silicates from the planetesimals.

This change of composition affects the thermal structure of the atmosphere. In particular, if the planet is located in a region where the temperature and pressure are suited for water condensation to take place, the release of latent heat modifies drastically the adiabatic temperature gradient. We discuss how this effect reduces the critical core mass and the implications this has for the type of planets that can be formed.

1) Internal Structure Code:

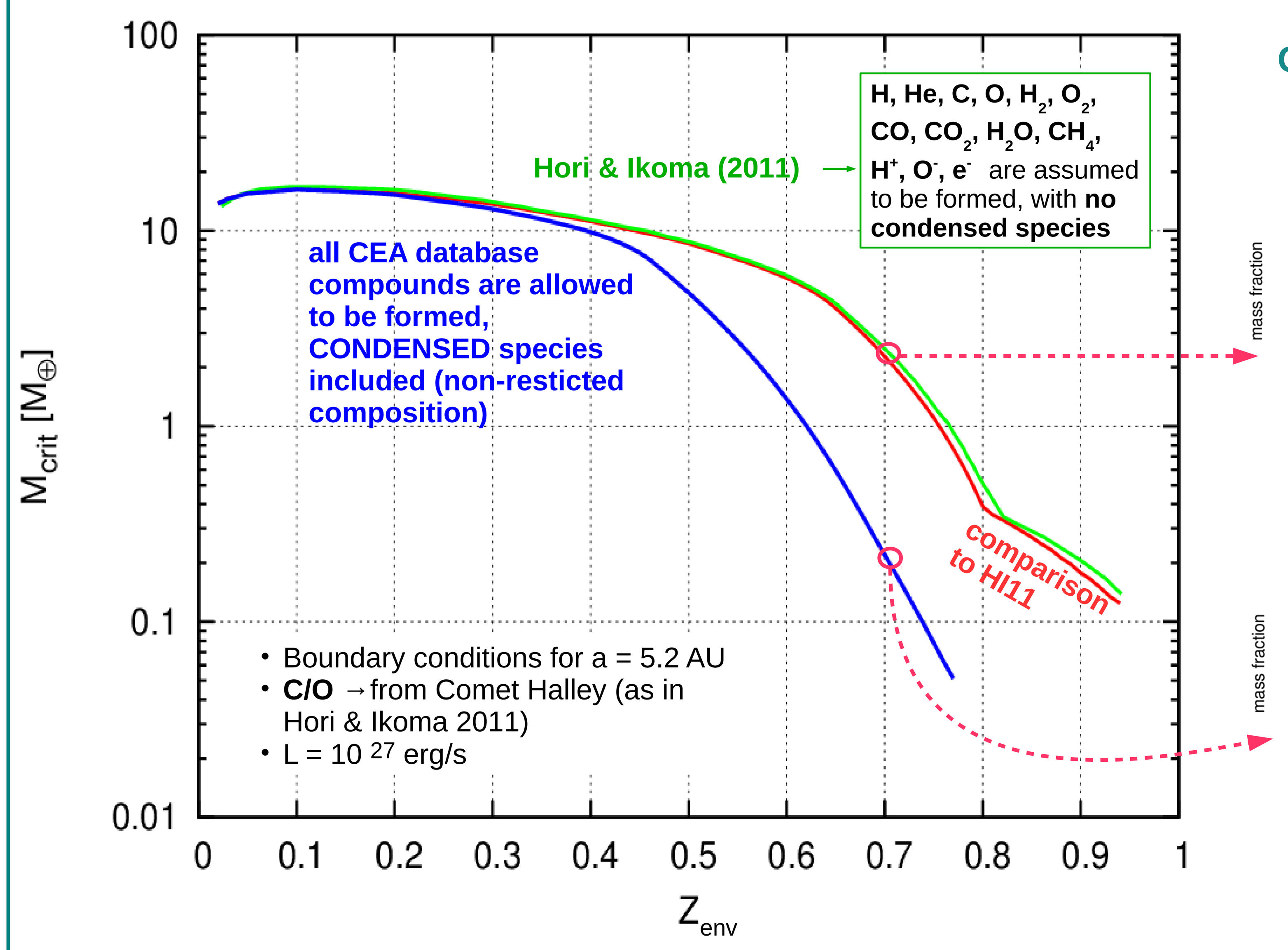
Solves the **internal structure equations** assuming a given luminosity.

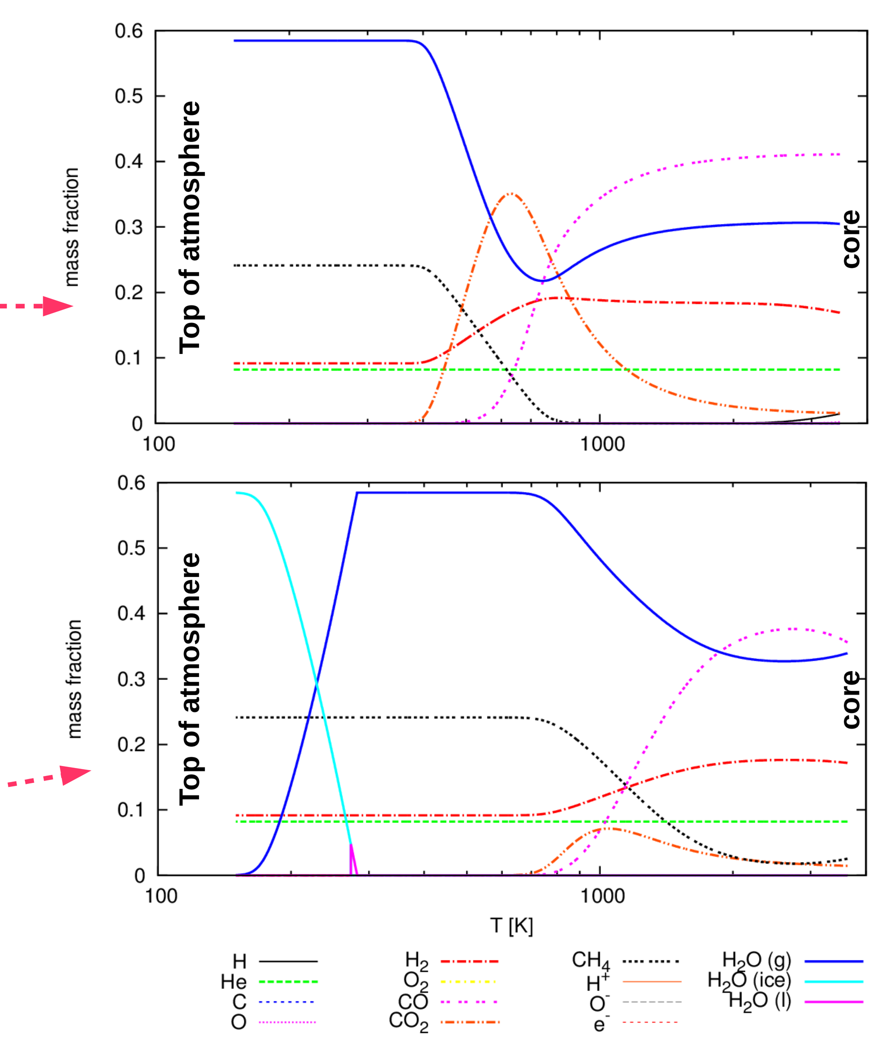
- **EOS**: software CEA (Chemical Equilibrium Applications) →
  - Solves chemical equilibrium for arbitrary gaseous mixture.
  - Ideal gas, but considers dissociation and ionization of compounds.
  - Includes condensation of some species, like H_2O in solid and liquid phase.
- **Opacities**:
  - Gas: tables of Alexander & Ferguson (1994) extended to consider all ranges of metallicities.
  - Dust: Semenov et al. (2003)

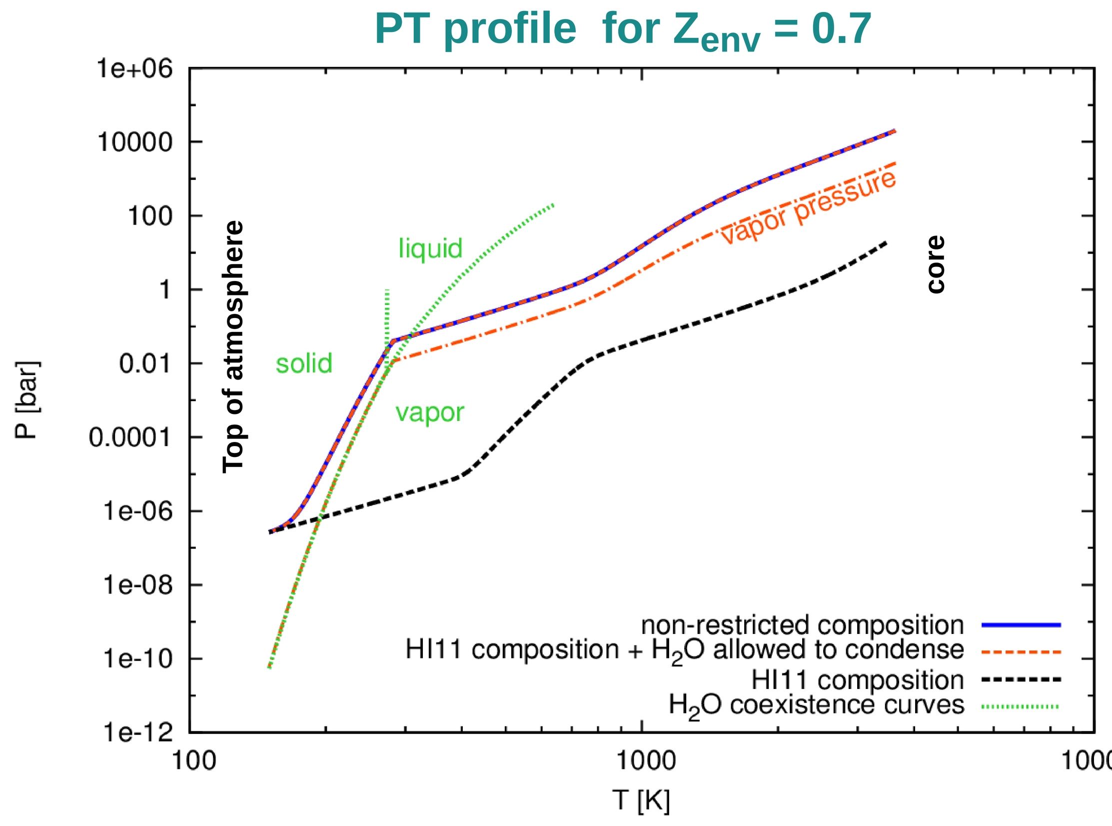
By solving them we compute the **critical core mass (M_{crit})** → maximum mass of the core able to sustain an envelope in hydrostatic equilibrium

for different **envelope metallicities** → $Z_{env} = \frac{M_{Z,env}}{M_{env}}$ → $M_{Z,env}$: mass of elements heavier than H and He in the envelope.

2) Results:







Note that

- When we restrict the composition to the one assumed by HI11, but we allow water to condense (orange curve), we obtain the same PT profile as in the non-resticted case.
- Water is being condensed from the top of the atmosphere until T = 282 K (for this Zenv), since in this temperature range the vapor pressure is equal to the saturation pressure of water given by the Clausius-Clapeyron relaiton (green curves).

Why the difference between the profiles explains the reduction of M_{crit}?

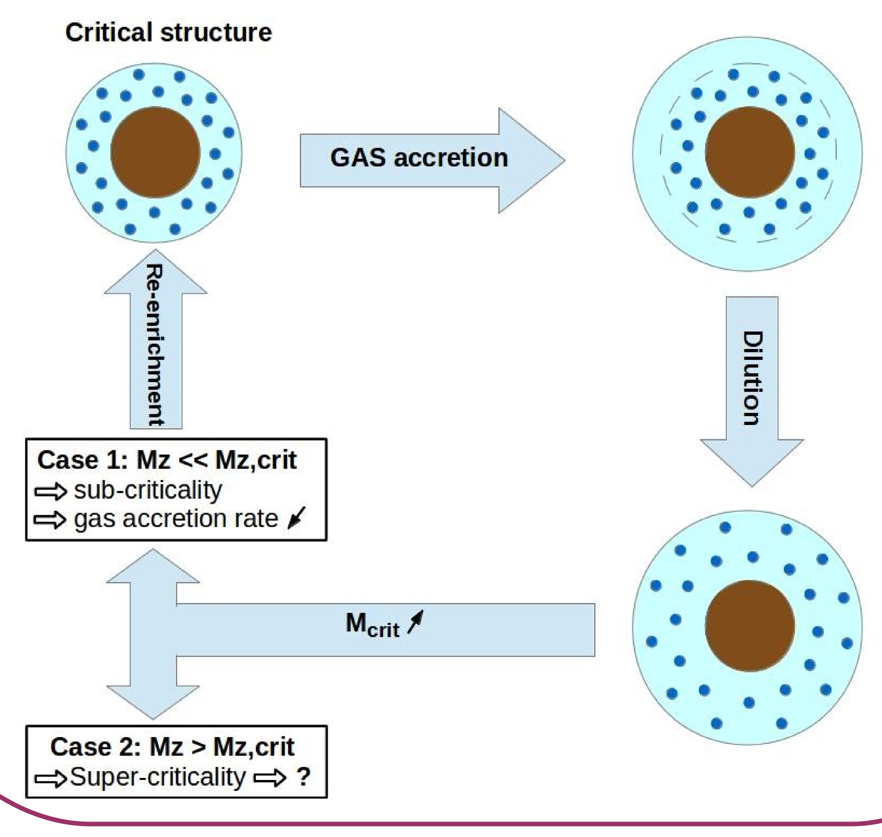
For the same T, the pressure is larger in the case where water condenses. This translates into a larger gas density for this case. This means that if we consider 2 planets with the same core mass, in the case where water condenses, the envelope will be more massive than in the case where water cannot condense, making the planet more prompt to become critical.

3) Discussion: possible post-critical evolution for enriched protoplanets

If a planet reaches the critical mass at a given Z_{crit}, two effects will appear. First, as a result of solid (i.e., planetesimal) accretion, the metal content of the planet (M_Z) increases. Second, as a result of gas accretion, the mean Z of the planet will change. According to Ikoma et al. (2000), the gas accretion rate at the critical point is similar, but slightly larger, than the planetesimal accretion rate. At the time when the critical core mass is reached, the accretion of solids and gas will lead to a decrease of the mean Z in the envelope. As a result, the critical core mass, as well as the total amount of heavy elements for the critical structure $M_{Z,crit}$, increase. A key point, for the immediate future of the planet is therefore to compare the increase of M_Z (resulting from the accretion of planetesimals) and the increase in the critical amount of heavy elements.

Thus, two possible scenarios could take place after the critical core mass is reached (see sketch below). In the first scenario (case 1), the increase of critical mass is faster than the increase of M_Z. In this case, the planet will become again subcritical, will not accrete anymore gas. Finally, as a result of planetesimal accretion, the metallicty may increase again. In the second scenario (case 2), the increase of critical mass is smaller than the increase of M_Z. In this case, the planet will remain super-critical, and might become a giant planet.

For planets located beyond the iceline, where water condensation can occur, case 1 is more likely to happen, given the larger increase in M_{crit} when the envelope dilutes compared to the case where water does not condense.



Conclusions:

- The critical core mass is reduced when the envelope is enriched in heavy elements. The results of Hori & ikoma (2011) were recovered.
- The reduction of M_{crit} is even larger if water is present in the outer parts of the envelope, and the boundary conditions are suited for H_2O to condense. In this case, the release of latent heat that takes place when condensation occurs, changes drastically the pressure-temperature profile, which translates into an increase of pressure for the same temperature. Thus, compared to the case where water is not allowed to condense, the density of the envelope in the case where water condenses is much higher, producing a more massive envelope for the same core mass.
- The post-critical evolution of an enriched protoplanet is not easy to infer. In principle, both giant planets and small enriched objects could be formed, and the last type of objects could preferentially result in the case where water condesation takes place. Quasi-static codes to study this properly is in a work in progress stage.

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