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How Can Giant Planet Composition Teach Us About Their Formation?

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Abstract

Since the detection of the first extrasolar giant over hundreds of extrasolar planets have been observed. Today, with better data and a relatively large sample of exoplanets we can reach the next level in exoplanetology studies, i.e. the characterization of planets around other stars and linking their physical properties with their origin. However, there is no simple way to relate the composition of a giant planet with its formation (and evolution) history. We suggest that even within the framework of the core accretion model [1] there is a large range of possible core masses and overall enrichment. This is also true for the disk instability model for giant planet formation [2]. The internal structure of the planets, i.e., the distribution of heavy elements, is not firmly constrained in either formation model and in fact can also change with time.

1. Giant Planet Formation - CA

The standard model for giant planet formation is core accretion (CA). In this model the formation of a giant planet begins with planetesimal coagulation and heavy-element core formation, followed by accretion of a gaseous envelope. Once the core mass and the mass of the gaseous envelope become about equal, a runaway gas accretion rapidly builds up the mass of the envelope while leaving the core at a nearly constant mass. Gas accretion then stops either by dissipation of nebular gas or by gap opening.

1.2. Predicted Composition - CA

Although the CA model is often linked with giant planets that are enriched with heavy elements compared to their star, in fact, CA does not predict a specific composition for the forming planet. The total heavy-element enrichment of the planet depends on (1) the planetary core mass, which, depends on disk properties, (2) on the amount of dust entrained within the accreted gaseous envelope, and (3) planetesimals (or even other planets) accreted subsequent to rapid gas accretion.

The total mass fraction of heavy elements in the planet can by given by

$$Z = (M_{core} + M_{Z\_env})/M_{planet},$$

where M_{Z_env} is the mass of heavy elements in the gaseous atmosphere. This simple relation demonstrates the dependence of the bulk composition on both the core mass and the abundance of the accreted gas. The relation implies that the final composition of a (massive) giant planet is strongly dependent on the accreted gas composition.

For relatively massive planets, the core contains only a very small fraction of the total mass. The predicted planetary Z therefore depends on the accreted gas composition that could be stellar, or dust-free or dust-enriched relative to the star. In fact, planets that are depleted in heavy elements compared to their host star could form as well. The gaseous envelope that is accreted could be depleted with solids (due to the processes of planetesimal formation, or solids migration) leading to a sub-stellar planetary Z.

Giant planets that are enriched with heavy elements compared to the star could form when cores are massive, when the accreted gas is enriched with solids, and when planetesimals are accreted at later stage of the planetary growth. It is therefore clear that CA could lead to the formation of planets with a wide range of final masses and compositions.

2. Giant Planet Formation - DI

An alternative model for giant planet formation is disk instability (DI). In this model giant planets form via fragmentation in proto-planetary disks. Various numerical simulations have now shown that proto-planetary disks can become unstable if they are sufficiently cool and/or develop a high enough surface density.

Once a local instability occurs, a gravitationally bound sub-condensation region is created. If this region is stable for a few cooling times, it contracts, and eventually evolves to become a gas giant plant.

2.2. Predicted Composition - DI

Recently, it has been shown that giant planets formed by this mechanism can also be enriched with heavy elements by various processes; enrichment from birth; mass-loss; and planetesimal capture [e.g., 3, 4]. Enrichment of massive protoplanets via planetesimal capture at large radial distances has been investigated by Helled and Bodenheimer [4]. Since the timescale of the pre-collapse stage is inversely proportional to the square of the planetary mass, massive protoplanets are expected to have less time to accrete solids.

Clearly, the final composition of protoplanets can change considerably depending on their birth environment. The large variation in compositions that are derived under different assumed physical conditions and processes could, in principle, explain the diversity in the inferred compositions of gas giant exoplanets. This is true also for the CA model.

3. The Distribution of Heavy Elements

While formation models provide estimates for the total mass of heavy elements within the planet, there is an uncertainty regarding the fate, and therefore the distribution, of the accreted heavy elements. While in the early stages, the planetesimals build up the core, as the planetary embryo accretes a gaseous atmosphere, the planetesimals do not go all the way to the center, but instead, are dissolved in the gaseous envelope. The deposition of heavy elements in the atmosphere depends on the sizes of the planetesimals, and on their compositions. Water is predicted to stay in the atmosphere [5] while the refractory materials tend to settle towards the center. In the DI model, there is still a fairly large uncertainty regarding the predicted internal structure of the forming planets.

In fact, the internal structure of a gas giant planet can also change with time. This can be a result of mixing, core erosion, and settling. The bulk composition, however, is likely to remain similar to the primordial composition, although one cannot exclude extreme scenarios in which the low-Z gaseous envelope is evaporated (or tidally disrupted) as the planet evolve.

4. Conclusions

- Both core accretion and disk instability can lead to a large range of compositions and core masses.
- There is no simple way to connect planetary composition with planetary formation.
- Future work on the predicted internal structure within the framework of the two formation models is required.

References

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