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GIANT PLANET FORMATION MODELS: THE CASE OF HD69830

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Abstract. We present formation models of the three Neptune mass planet system around HD69830. We first show that the formation of this system is very unlikely in the framework of the disk instability model. We then derive formation models based on the extended core-accretion model, taking into account migration as well as disk evolution. We show that the two outermost planets have started their formation process at large distances from the central star, and have therefore accreted a lot of icy planetesimals. We finally calculate the thermodynamical conditions inside these two planets, and show that water is likely to exist there under the form of a super-critical fluid.

1 Introduction : the HD69830 system

The three Neptune-mass planetary system orbiting HD69830, a 4-10 Gyr old nearby star with a mass estimated at $0.86 \pm 0.03 M_\odot$, has been discovered through high precision measurements obtained with the HARPS spectrograph installed at La Silla, Chile (Lovis et al. 2006). The three planets, planets b,c and d, are located at 0.0785, 0.186 and 0.63 AU from the central star, and their minimum masses are equal to 10.2, 11.8, 18.1 $M_\oplus$ respectively. Interestingly, the outermost planet of this system appears to be located near the inner edge of the habitable zone, where liquid water could exist. This system, with three sub-Neptune mass planets within 1 AU, represents a major extension of the currently known parameter space occupied by extrasolar planets. It is also a considerable challenge for the planet formation models.

2 Formation by disk instability

The two main planet formation models are the disk instability (DI) model and the core-accretion model. In the DI model, gravitational instabilities directly lead to the formation of clumps that eventually evolve to form giant planets. In the case of the present planetary system, this formation mechanism can be ruled out for two reasons. First, the inner regions of the disk are too hot for gravitational instabilities to take place. Second, gravitational instabilities at larger distances produce clumps with masses much larger than those considered here (e.g. Boss 2001). Hence, even if subsequent migration brings these clumps within 1 AU, they would be much more massive than the planets considered here. Indeed, at least for the two outermost planets, we show that mass loss from evaporation induced by the host star's high energy radiation is negligible.

It has been suggested that low mass planets could form in the framework of the DI model, if one assume the presence of a FUV/EUV source close to the formation site (e.g. a *close-in* O star (Boss 2006)). If such an external source is present, photoevaporation indeed occurs at distance larger than $r_\mathrm{e} \propto GM_\mathrm{star}/c_s^2$, where M_star is the mass of the central star, and c_s is the sound speed of gas heated up by the FUV/EUV flux. Estimations of r_e depend on the energy of the incoming flux, and range from 5 AU for EUV to 50 AU for FUV (Johnstone et al. 1998). In the case of the Solar System, these values are consistent with a possible evaporation of Uranus and Neptune, and the preservation of Jupiter's and Saturn's gas envelopes. Given the mass of HD69830 (close to solar), the photoevaporation radius r_e should be similar, and it seems impossible to photoevaporate the outermost planet (located well below the lowest estimate of r_e) due to FUV or EUV.

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It has been more recently claimed that $r_{\rm e}$ could be much lower, as low as 1 AU for EUV flux and 10 AU for FUV flux (Adams et al. 2004). In that case, the evaporation of HD69830d by an external source would be marginally possible, but it becomes then difficult to explain the survival of Jupiter's atmosphere. The only explanation would require an *EUV flux* in the HD69830 system, and a *FUV flux* in the case of the Solar System.

Finally, we note that this EUV flux in the HD69830 system would have to start after the outermost planet has reached a location close to its actual one (migration requires the presence of a large amount of gas inside the disk). Moreover, in the presence of a strong evaporating flux, the time spent by a jupiter mass planet at a mass of the order of the one of HD69830d is very short (Baraffe et al.2004, 2006). Therefore, it is necessary to highly fine tune both the start and the stop time of the EUV flux in order to reconcile a DI/photoevaporating model and the present system. The HD69830 system thus seem to be very difficult to accommodate within the DI model.

3 Formation by nucleated instability

In the core-instability model, a solid core is formed first by the accretion of solid planetesimals. As the core grows, it eventually becomes massive enough to gravitationally bind some nebular gas, forming a gaseous envelope in hydrostatic equilibrium. The further increase in core and envelope masses leads to larger and larger radiative losses, which ultimately prevent the existence of an equilibrium envelope. Runaway gas accretion occurs, rapidly building up a giant planet (e.g. Alibert et al. 2005a).

In the framework of this model, the *in-situ* formation of cores large enough to trigger the runaway gas accretion, and consequently the *in-situ* formation of *close-in* giant planets, is prevented by the sheer lack of solid material that close to the star. On the one hand, low mass disks simply lack the necessary amount of solids, while on the other hand more massive disks with similar lifetimes are too hot for solids to condense at these short distances. Thus, to reach their present mass, the planets orbiting HD69830 must have swept planetesimals over distant regions of the disk. Therefore, the discovery of this system of hot-Neptune planets implies (if there were any doubts left) that significant planetary migration had to occur.

In order to compute the formation and the evolution of this system to the present day and infer the structure and composition of the three planets, we use the extended core accretion model which takes into account the migration of the proto-planets as well as the evolution of the disk. We also consider the evolution of the new born planets to the present day by taking into account the effects of irradiation and evaporation due to stellar radiation. Our entire approach has been extensively described elsewhere (Alibert et al. 2005a, 2006; Baraffe et al. 2004, 2006), where the reader is referred for more details. Using these models, we performed a large number (few tens of thousand) of simulations to find all initial conditions leading to a planetary system comparable to this one. Assuming a central star of 0.86 $M_\odot$ and of slightly sub-solar metallicity (Lovis et al. 2006), we start our calculations with a protoplanetary disk and seed the three planets by means of three embryos of 0.6 $M_\oplus$ each. We explore the different disk characteristics (mass and lifetime) and initial locations of the three embryos leading to the observed characteristics of the three planets.

Due to their migration, planets eventually encounter the wake created by the preceeding planet. As the planet encounters a region depleted of planetesimals by the passage of a previous body, the accretion rate of solids is vanishing, leading to the suppression of the main heating source and the planet can accrete gas (Alibert et al. 2005b) at a rate essentially given by its Kelvin-Helmholtz timescale (Ida & Lin 2004). Note that the absence of solids in the innermost regions of the disk (inside $\sim$0.35 AU), where the temperature exceeds the evaporation temperature of silicates ($\sim$1600 K), leads to a similar effect.

Our calculations show that the innermost planet (solid lines in Fig. 1, left) starts from 3 AU and grows by accreting essentially rocky planetesimals. At the time it enters the innermost regions of the disk (below 0.35 AU), the accretion rate of solids drops dramatically triggering the accretion of gas (Alibert et al. 2005b). The planet reaches its final position at the time the disk vanishes and consists, at the end of its formation, of a solid core of $\sim$10 $M_\oplus$ surrounded by an envelope of $\sim$5 $M_\oplus$. The second embryo (dotted lines) starts at 6.5 AU and accretes planetesimals until it enters the region already depleted by the innermost planet (3AU). This depletion again triggers the accretion of gas, leading to a planet consisting, before the evaporation phase, in a rocky/icy core of $\sim$ 7.5 $M_\oplus$ and a gaseous envelope of $\sim$ 7.5 $M_\oplus$. Finally, the outermost planet's embryo (dashed lines) starts at $\sim$ 8 AU (well beyond the iceline) and accretes a large amount ($\sim$ 60 %) of solids in form of icy planetesimals. At the time the growing planet enters the region of the disk already depleted by the second planet, gas accretion is again triggered. Assuming a standard ices-to-rocks ratio of 4, the final planet consists of a $\sim 10 M_\oplus$ core ($\sim 5.2 M_\oplus$ of rocks and $\sim 4.8 M_\oplus$ of ices), surrounded by a gaseous envelope of $\sim 8 M_\oplus$. For this planet, evaporation is negligible (see below).

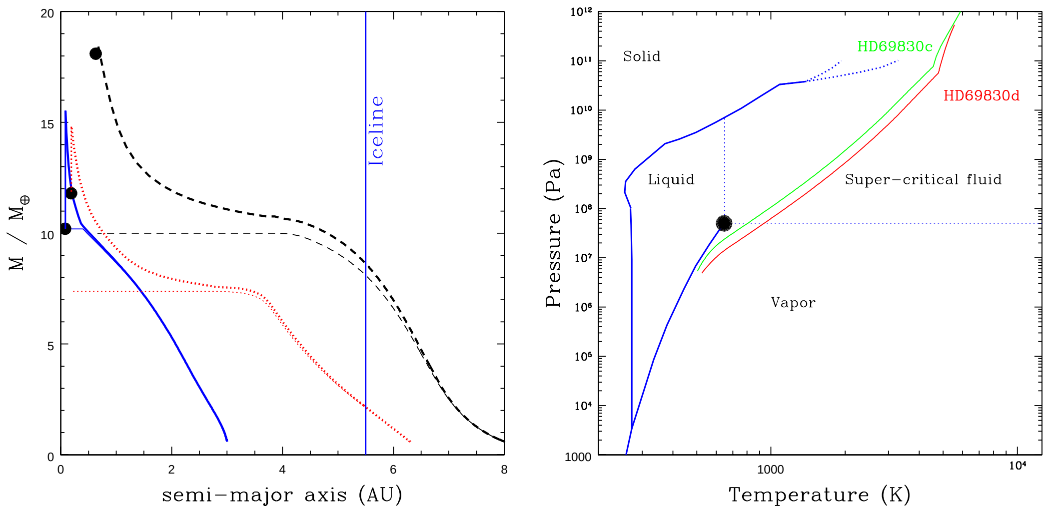

Fig. 1. Left Formation/evolutionary tracks of the planetary system orbiting HD69830. The total mass (thick lines) and the core mass (thin lines) for the three planets are given as a function of semi-major axis which is decreasing with time as a result of migration. The iceline is indicated by the vertical line. The minimum mass and semi-major axis derived from the observations are indicated as big dots. The solid lines correspond to the innermost planet, the dotted lines to the middle one, and the dashed lines to the outermost one. The vertical lines at 0.08 AU and 0.18 AU reflect the evaporation of the two innermost planets during 4-10 Gyr, the estimated age of the system. **Right** Thermodynamical conditions inside planets c and d and simplified phase diagram of water. The big dot indicates the position of the critical point. The two heavy dotted curves at high pressures give the likely location of the melting curve (Lin et al. 2005).

4 Evolution and evaporation

We have calculated the evolution/evaporation of the three planets. For this, the initial internal compositions are the one obtained at the end of the formation phase (see above). The incident radiation of the parent star, which modifies the internal structure and the cooling rate of planets is taken into account, as well as the mass loss due to the evaporation of the outermost layers of the planet's envelope heated by the incident stellar high energy flux. The evaporation rate was chosen to be 1/20 the maximal escape rate of Lammer et al. (2003), a value obtained by various recent detailed hydrodynamical calculations (Tian et al. 2005, Yelle 2004), and consistent with lower limits inferred from observations (Vidal-Madjar et al. 2003).

The effect of irradiation and evaporation is found to be completely negligible for the planet d and to lead to only a small (5%-10%) mass loss for planet c (see vertical line at 0.18 AU in Fig. 1, right). For planet b, however, it is significant (vertical line at 0.08 AU in Fig. 1). Within a few Gyr, essentially all its envelope is evaporated, leaving behind a solid core with only a tiny (less than 2 $M_\oplus$) gaseous atmosphere. Calculations done with slightly different initial conditions (core and envelope mass), yield similar results. The radius of a rocky core of 10 $M_\oplus$ is $0.18 R_{\rm J}$ (radius of Jupiter). which gives a lower limit for the expected radius of this planet. In the case it was able to retain even a tiny atmosphere its radius will be larger: for an envelope mass of $\sim 2 M_\oplus$, the radius would be increased to $\sim 0.45 R_{\rm J}$. The radii of the two outermost planets are found to be 50-60% $R_{\rm J}$, depending on the precise composition of the planet's core and the age of the system.

Figure 1, right, shows the thermodynamical conditions inside planets c and d, after 4 Gyr, the minimum age of the system, (the results after 10 Gyr are very similar), together with a simplified phase diagram of water. For these two planets, the temperature and pressure are such that water is likely to exist under the form of a super-critical fluid.

5 Conclusion

Our calculations provide a fully consistent scenario for the formation and evolution of the planetary system around HD69830. We show that the innermost planet consists of a rocky core, with possibly a tiny gaseous envelope, whereas the two outermost planets are made of a central rocky core, a shell of super-critical fluid water and a gaseous envelope. From the calculations presented we can infer the following general scenario for the formation of the system. All three planets start by accreting planetesimals and very little gas as they migrate inwards until they reach a region depleted in solids either by the passage of a previous planet or because of too high temperatures. The main heating source being suppressed they essentially accrete gas at a rate given by their Kelvin-Helmholtz (KH) timescale (Alibert et al., 2005b, Ida & Lin 2004). To remain of Neptune-mass without requiring unlikely timing with the disapearence of the disk, a given planet must enter this depleted region when its KH timescale is of the order of the lifetime of the disk which corresponds to a mass of order 8-12 $M_\oplus$ (Ida & Lin 2004). For the three planets to collect this mass of heavy elements implies a significant amount of migration of the growing cores.

An observational test of the present formation and evolution scenario would be the determination of the mean density of the planets. While difficult from the ground, such observations are within reach of HST, COROT or KEPLER. Even if the present system does not lead to observable transits, it is likely that similar, transiting Neptune-mass systems will be discovered in a near future. Confrontation of the present theory with such observations will improve dramatically our understanding of planet formation.

Finally, Spitzer observations of the HD69830 system have revealed the presence of micron sized dust at distances lower than 1 AU from the central star (Beichman et al. 2005). This may result from the presence of an asteroid belt, or of a large size comet ($\sim$1000 km), see Beichman et al. (2005). Preliminary calculations have shown that the passage of the three forming planets may largely but not totally eject the asteroids belt. This latter, if present before the formation of the planets, would be able to survive the formation process. Interestingly, we note that dust is observed in regions in mean motion resonnances with the outermost planet (1:2 and 1:3), that may excite the asteroids, leading to collisions and dust production.

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