Maximum Embedded Equilibrium Masses for close-in Giant Planets

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1 Introduction

Current detections show quite a number of exoplanets with semi major axes below 0.1 AU or orbital Periods below 10 days. This poses a challenge for conventional planet synthesis methods (e.g. Ida & Lin 2004; Mordasini et al. 2008) because these depend on the knowledge of the disk structure. However, at such close proximity little is know about the structure of disks. Some observations indicate central gaps around the star (Hillenbrand et al. 1992, Tuthill et al. 2001, Calvet et al. 2002) but few information is available. Nevertheless, even at distances smaller than 0.03 AU some planets have been detected (e.g. see Pont et al. 2007, Rivera et al. 2005, O'Donovan et al. 2007, Gillon et al. 2006, Butler et al. 2004). This shows that at least in some cases there must have been gas at these distances. Even in the case of migration, gas is needed close to the planet's orbit to make the planet migrate.

2 Aims & Methods

We have constructed the set of all solutions to the planetary structure equations for gas giants in hydrostatic force balance, i.e. with sub-critical cores for the given conditions. For each location (T_{orb}, host star, $\dot{M}_{pl}$) the core mass and central pressure was varied over many orders of magnitude to find all solutions. Locations span the following ranges: orbital periods from 1 to 4096 days, host star masses from 0.4 to 2 $M_\odot$, and planetary accretion rates from 10^{-2} M♁ yr^{-1} to 10^{-6} M♁ yr^{-1}. The full set of solutions we term CoRoT survey Mark 3. It contains a several million planetary models.

In the case of hot planets it has been shown that the critical core mass can be very large and is therefore probably rarely exceeded (see Broeg & Wuchterl 2007). Therefore we expect close-in exoplanets to represent approximately a sub-sample of our hydrostatic solutions, with the best resemblance if all static structures are produced in nature and in roughly equal proportions.

3 Results

The results show many a priori unexpected properties, such as the planetary mass range of most solutions, bi- or trimodal mass distributions, and three classes of gas giants separated by orbital period. We could identify three different peaks in all mass distributions that stem from the same three physical principles: self-gravity in the roche lobe, compact objects, and very low values of the adiabatic temperature gradient in certain regions of the P-T-plane. Here we will focus on the concept of the **M**aximum **E**mbedded **E**quilibrium **M**ass (MEEM). For the full results we refer to Broeg (2009).

Our calculations show an upper mass limit for embedded hydrostatic proto-planets. This we term maximum embedded equilibrium mass (MEEM). While the existence of a MEEM for cold objects is obvious, the value is not. The mass limit depends strongly on location parameters such as orbital period. However, in the entire survey practically all locations have a MEEM below 13 Jupiter masses-i.e. in the planetary mass range! This is a non-trivial result: the only absolute mass range in the calculations is given by the host star mass. Therefore we decided to study the dependence of the MEEM on location parameters. Fig. 1 shows the MEEM as a function of T_{orb} for different values of $\dot{M}_{pl}$ and host star mass together with detected exoplanets. For the classification into class G, H, and J see Broeg (2007). One can see the strong increase in MEEM from 64 days orbital period to 1 day. The dependence of the MEEM on T_{orb} naturally explains the lack of very massive planets having orbital periods below 64 days. At very small orbital separations, the MEEM becomes very large again.

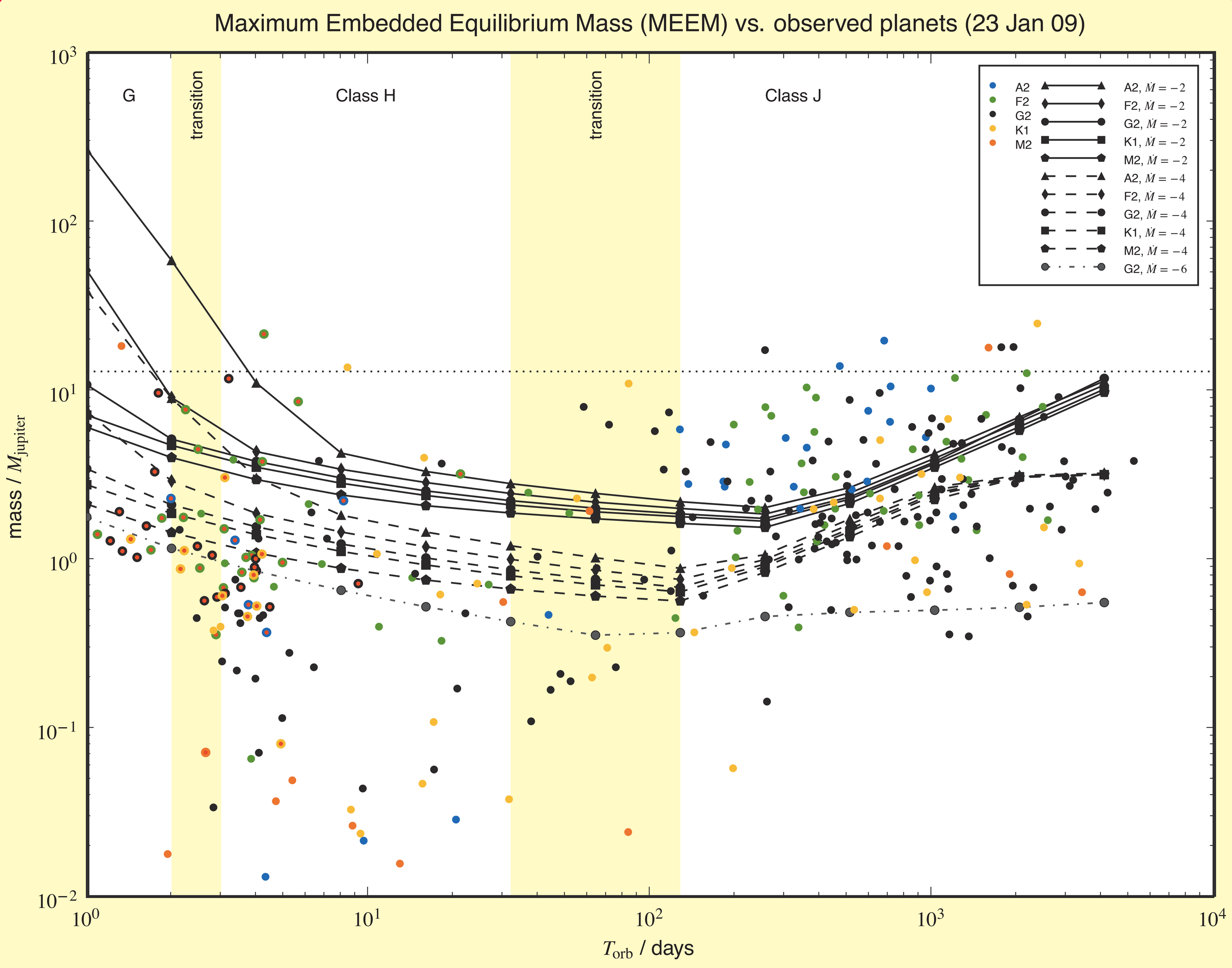

Fig. 1: Maximum embedded equilibrium masses (MEEM) vs. toady's exo-planets (RV & transit planets from exoplanet.eu; circle color indicates host star mass, red dots flag the transit detections). Dependence on orbital period for different host stars and accretion rates: The solid grey lines represent the MEEM for the highest accretion rate. Top to bottom they have been calculated for a 2, 1.45, 1, 0.8, and 0.4 solar mass host star. The dashed grey lines show the resulting upper mass limit for lower accretion rate ($\dot{M}_{pl}$ = 10^{-4} M♁ yr^{-1}) – this corresponds to more normal conditions. Obviously most exo-planets lie below the dashed lines for Class G and H. Beyond the transition region to Class J planets, the upper mass limit becomes meaningless. This is again clearly reflected in the observed data (see text).

Motivated by the rather good match of observed upper mass limits and MEEM for classes H and G, we compared our mass distributions of very close-in planets (below 0.2 AU) with results obtained by Monte Carlo planet synthesis calculations (from Mordasini et al. 2008). Using our normal procedure we could qualitatively obtain the same bimodal distribution. To get a better fit, we took the resulting core-mass distribution from the planet synthesis calculation and replaced our log-constant core mass distribution with it. The comparison is shown in Fig. 2.

In addition, we have used all our results to produce mixed or averaged mass distributions for a typical CoRoT field (in this case a galactic center star distribution). The results for different T_{orb} are shown at the bottom of this poster. The very sharp peaks are caused by poor sampling in $\dot{M}_{pl}$. In reality, the maximum $\dot{M}_{pl}$ value will be continuously distributed thus smoothing the sharp peaks. This is simulated using a moving average (red line).

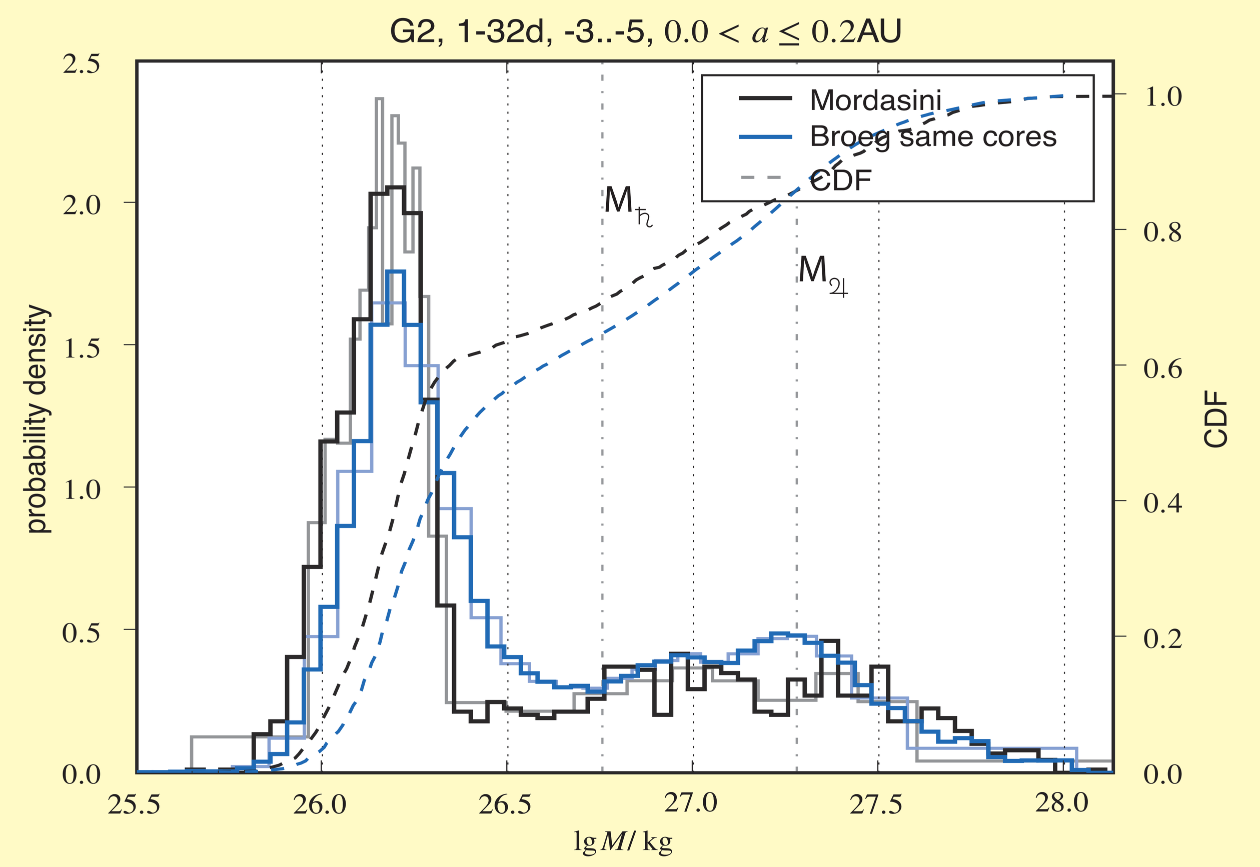

Fig. 2: Theoretical mass distribution for planets having orbital periods below 32 days calculated by two completely different methods. The dark solid lines give the binned mass distribution (histogram of planet masses), the light solid lines have been obtained by differentiating the cumulative distribution function (CDF). The dashed lines show the corresponding CDF. Black: planet population calculated by Monte Carlo planet synthesis for a solar type host star (Mordasini et al. 2008) having a<0.2 AU. Blue: the planet population obtained by calculating all hydrostatic equilibria. Contrary to the normal procedure we have replaced the log constant core mass distribution with the core mass distribution obtained by Mordasini et al. (2008). The final distributions are quite similar despite a completely different methodology. We get the best fit using only planetary accretion rates from 10^{-3} M♁ yr^{-1} to 10^{-5} M♁ yr^{-1}.

4 Conclusions & Discussion

The results indicate that the hydrostatic equilibrium phase embedded in a protoplanetary disk is very important for the evolution of Pegasi type planets. The upper mass limits given as the largest occuring masses in our solution manifolds appear to be relevant for the observed planets. This concept we term the **M**aximum **E**mbedded **E**quilibrium **M**ass (MEEM). It is plotted in Fig. 1 and should be an upper envelope for the planet masses only if significant mass gain is not achieved after the cores become super-critical or planetesimal accretion stops. Among the detected exo-planets, few planets exceed their respective MEEM value. Furthermore it is clear that the classification into classes G, H, and J is useful. Especially the transition from class H to J clearly marks the end of applicability of the MEEM criterion. This is caused by two effects: 1) The critical core mass becomes small enough for class J planets so that it is relatively easily exceeded. Beyond the critical core mass the MEEM is no longer a valid upper mass limit. Nevertheless, it might still be a characteristic mass in the mass distribution—i.e. the mode. 2) The compact peak becomes less massive than the self-gravity peak. We believe that this has grave consequences for the stability of the envelopes (see Broeg 2009 for an in-depth discussion about the physical origin of the peaks in the mass spectrum).

So far we have not discussed how migration affects the results. As every hydrostatic structure represents a snapshot in the evolution of a hypothetical planet, the question if it is at that moment undergoing orbital migration is secondary. Therefore these results should be independent of the type and speed of migration. Nevertheless, a few caveats have to be considered: If the migration, e.g. type I, is so rapid that the planet cannot adjust its internal structure fast enough to the changing boundary conditions, the model breaks down. Equally, a gas giant planet of class J that has grown a super-critical core and that subsequently migrates into regions of class H or G planets will evidently break the argument for sub-critical cores in that regime. While weakly super-critical cores might become sub-critical again by a strong increase in $\dot{M}_{pl}$, this is not likely to happen for very massive cores.

When comparing these results with full-fledged planet synthesis calculations the good agreement at small separations was unexpected. For the very close-in planets, the mass distribution immediately looked similar. When also using the correct core mass distribution, the resulting mass distributions are very much alike (see Fig. 2). Note that we have removed planets having an envelope mass fraction <1% because the equilibrium approach naturally fails to work for terrestrial planets. While we are not quite sure why the agreement is so good, a few conclusion can be drawn from this fact. It appears that massive planets from outside do not migrate very close to the star after reaching the critical core mass (this is actually confirmed by the Monte Carlo simulation). Otherwise we would see more massive planets above the MEEM in Fig. 1 and get a mismatch for massive planets in the mass distributions. Furthermore, the majority of core-envelope structures allowed by the planetary structure equations seems to be realized in nature—at least in this regime very close to the star.

In summary, the MEEM concept helped us to understand the upper envelope of the observed planet population masses at very small orbital separations. Furthermore, the existance of a MEEM could help in a future definition of an upper mass limit for planets vs. Brown Dwarfs removing the need for the rather arbitrary value of 13 M♃.

5 References

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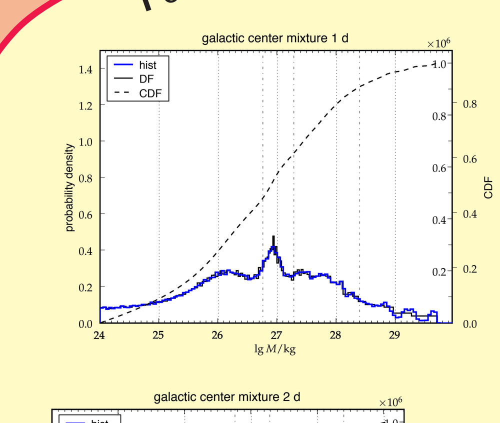
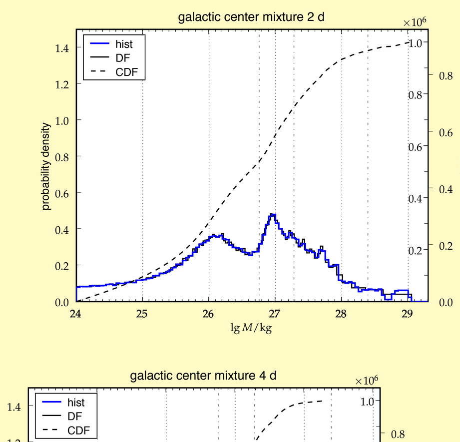
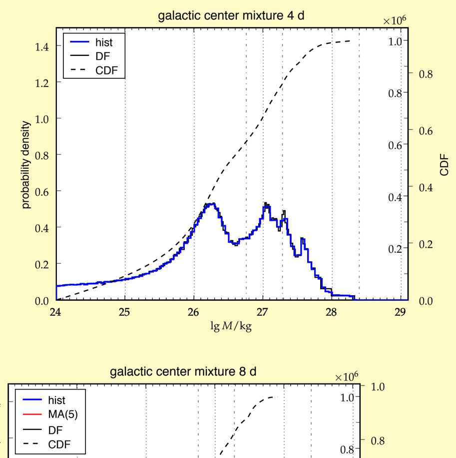
T_{orb} = 1 day







CoRoT galactic center field mixtures

T_{orb} = 64 days