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Dynamical Simulations of HD 69830

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Abstract. Previous studies have developed models for the growth and migration of three planets orbiting HD 69830. We perform n-body simulations using MERCURY (Chambers 1999) to explore the implications of these models for: 1) the excitation of planetary orbits via planet-planet interactions, 2) the accretion and clearing of a putative planetesimal disk, 3) the distribution of planetesimal orbits following migration, and 4) the implications for the origin of the observed infrared emission from the HD 69830 system. We report preliminary results that suggest new constraints on the formation of HD 69830.

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1. Observations

Radial velocity observations of HD 69830 by Lovis *et al.* (2006) reveal a system of 3 intermediate-mass planets ($M \sin i = 10.2$, 11.8 & $18.1 M_{\oplus}$ respectively) orbiting close to the central star (semi-major axes of 0.08, 0.19 & 0.63 AU), with eccentricities 0.10 ± 0.04, 0.13 ± 0.06 & 0.07 ± 0.07 respectively. Whilst these eccentricities are modest when compared to the observed eccentricity distribution of the extra-solar planets (Ford *et al.* 2007), they are significant enough (especially for the inner two planets) to demand explanation.

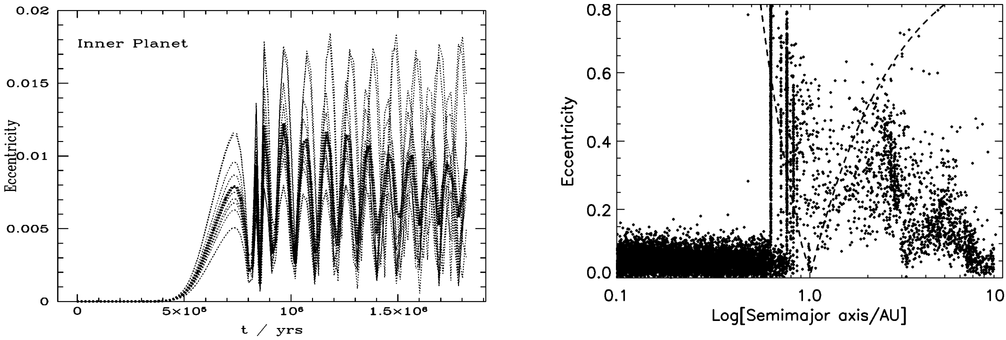
Infrared Spitzer observations by Beichman *et al.* (2005) find a strong SED excess at 8 and $35\mu m$, but no excess at $70\mu m$, indicative of a system containing warm dust ($\sim 400K$) orbiting close to the central star ($\sim 1AU$).

2. Previous Models

Planetary Growth. Previous research (Alibert *et al.* 2005, Alibert *et al.* 2006 & Baraffe *et al.* 2006) led to a detailed semi-analytic model able to explain the mass growth and migration of the three planets, starting from low mass cores ($\sim 0.6 M_{\oplus}$) at large semi-major axes (~ 3, 6 & 8 AU respectively) which grow as the planets migrate inwards towards the observed semi-major axes.

IR Emission. The observed IR emission requires significant amounts of dust at ~ 1 AU. Several models for the parent population of this dust have been proposed, including, (i) the steady-state evolution of an eccentric disk with pericentre near 1 AU, (ii) A recent dynamical instability which results in planetesimals from an outer belt being thrown inwards, (iii) the capture of a super-comet onto a circular orbit at ~ 1 AU, and (iv) a massive cometary population.

Wyatt *et al.* (2007) considered a circular primordial planetesimal belt evolving in a quasi-steady state at 1 AU. They found that collisional processing would have removed most of the belt's mass over the > 2 Gyr age of the star. Hence any parent population for the dust would have to be located at a greater semi-major axis than this and/or occupy more eccentric orbits.



(a) Planet-planet interactions excite eccentricity growth. E.g. Inner Planet: HD69830b

(b) Capture into MMRs excites, shepherds and scatters planetesimals.

Figure 1. The effect of migration on planetary eccentricity and the planetesimal distributions.

3. Our Model

The initial conditions for the planets and the rates for the subsequent mass growth and migration are all modelled after those given in Alibert *et al.* (2006). The planetary embryos of $0.6M_\oplus$ are started at 3, 6.3 & 8 AU and they then migrate, growing as they travel inwards along the prescribed paths (data kindly supplied by Yann Alibert).

The planetesimals are initially distributed in a disk ranging over $0.1 - 9$ AU, obeying a $\Sigma \propto a^{-3/2}$ profile, with $2 < i > = < e > = 0.05$. For simplicity of numerical integration, the planetesimals are assumed to be test particles (although a certain physical size is assumed to implement the gas-damping module). The gas damping of planetesimals uses a 3-D disk model to allow for the vastly increased damping timescales associated with highly inclined and/or eccentric orbits, with the analytic damping rates being taken from Rafikov (2006) and Mandell *et al.* (2006)

4. Planetary Eccentricities

In an undamped minimum mass model, the eccentricity excitation during planet migration (See Fig 1(a)) is an order of magnitude lower than the best fit eccentricities from radial velocity observations (See §1). To explain the observed eccentricities via this model would require that the planetary masses be increased by a factor of at least 5 times that of the minimum masses consistent with R.V. observations, implying that the system would be highly tilted, i.e. almost face-on systems with inclinations ~ 5 degrees.

Applying gas damping to the planets during their migration makes the problem significantly worse: gas-damping from a disk with a lifetime of 2 Myr (as used in Alibert *et al.* 2006) would leave the eccentricities damped to 2 orders of magnitude below the observed values.

5. Planetary Accretion Rates

In our models with no eccentricity damping, the accretion rate onto the inner planet during migration is two orders of magnitude greater than that onto the outer planet. This results in the inner planet accreting 65% of the solid disk mass between 1 and 9 AU, suggesting that it would accrete around $100M_\oplus$, far in excess of the minimum observed mass for the inner planet, whilst the outer planet, observed to be more massive than the inner planet, accretes less than $1M_\oplus$, far less than required from observations.

Including gas damping of planetesimals eccentricity reduces the difference in accretion rates between inner and outer planets to one order of magnitude, but now tends to make both planets accrete rather less ($\sim 1M_{\oplus}$) than required ($\sim 10M_{\oplus}$). The collision rate is much reduced because the shepherded planetesimals are now efficiently damped and hence do *not* have high enough eccentricities to be on orbits which cross with that of the inner planet, hence avoiding collisions.

Both of these results appear to be at odds with the results of the Alibert *et al.* (2006) model in which all the planets have similar core masses. As long as no significant physical processes have been omitted from our n-body simulations, we would expect them to give a more intrinsically realistic history for the plantesimal accretion than that given by a semi-analytic model as used in Alibert *et al.* (2006). This suggests that the semi-analytic model would need to be altered to try and include the physics effects of shepherding, damping, etc.

6. Scattered Planetesimal Disk

Following the migration of the planets through the disk, we investigate the properties of the scattered planetesimal disk to understand whether it could provide the parent bodies needed to generate the observed IR emission. The outcomes of some selected simulations are displayed in Figure 2. In the top row we compare and contrast the results for planets migrating and growing to the standard observed masses with the results for planets of 5 times this mass. The left-hand plot shows the a-e distribution of planetesimals after migration in the 5× mass mode, whilst the eccentricity and pericentre histograms compare the results for these massive planets with those results for systems with the standard mass planets. In the bottom row we plot the results when we take into account the effect of gas-damping on the planetesimals, with the histograms again allowing comparison of the standard and 5-times-as-massive systems.

In all cases, irrespective of planetary masses or eccentricities or the presence/absence of gas-damping in the simulations, a substantial fraction of the total solid disk mass (10–15%, i.e. $\sim 15M_{\oplus}$) will remain in the system in an excited state with $q \geqslant 1$ AU, thus forming an extended eccentric disk, potentially acting as a reservoir population for the generation of dust at semi-major axes $\sim 1AU$.

Whilst the *amount* of remaining material is insensitive to the details of assumed masses or damping, the distribution of *eccentricities* in the remaining planetesimals *is* sensitive to the assumed planetesimal damping rate (see Figure 2). The average final planetesimal eccentricities ranging from 0.13 (minimum-mass planets stirring planetesimals, efficient gas damping) to 0.47 (more massive planets stirring planetesimals, no damping).

In addition we note that the introduction of gas damping on the planetesimals will have the effect of "size-sorting" the system. By this we mean that the larger planetesimal bodies (which contain the majority of the mass in the system) are affected *least* by the gas-damping and hence can remain in highly eccentric orbits. In contrast, the smaller planetesimals will be easily damped and quickly forced to preferentially occupy low eccentricity or circular orbits.

7. Conclusions

- Assuming the planets form on circular orbits, the basic model of Alibert *et al.* (2006) does not naturally explain the observed planetary eccentricities. Additional mass is needed in the model, either in terms of increased planetary masses and/or additional embryos.

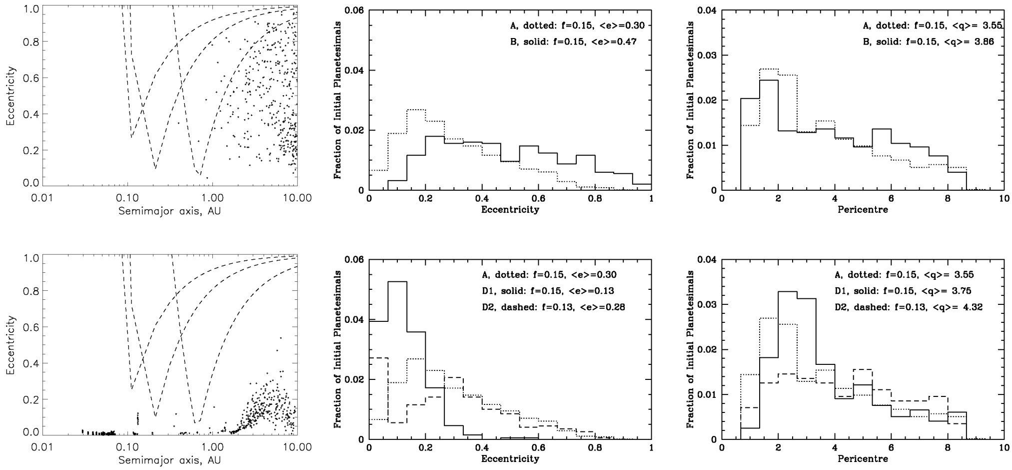


Figure 2. Comparative results plots for selected simulations: [Top Row] - Planetesimal distributions after stirring by different planetary masses: Increased (5×) Planetary Masses - Solid Histograms, Standard Masses - Dotted Line. [Bottom Row] - Results when gas drag acts on 100km planetesimals: Gas Drag on Planetesimals + Standard Planet Mass - Solid Histogram, Gas Drag on Planetesimals + 5× Standard Planet Mass - Dashed Histogram, Standard Zero Drag - Dotted Line. Left Hand Column = Planetesimal Eccentricity-v-Semi-Major Axis Plots; Central Column = Eccentricity Histograms for planetesimals with $q < 1$; Right Hand Column = Pericentre Histograms for planetesimals with $q < 1$. f is the fraction of total planetesimals which survive in the system with $q > 1$ AU.

- Gas damping of planetesimals serves to decrease the proportion of planetesimals with high eccentricities but does not decrease the size of the scattered population.
- Gas damping also works to "size-sort" the planetesimals, circularising small planetesimals whilst allowing the larger bodies to remain on more highly eccentric orbits.
- Clearing of the disk outside 1 AU is *inefficient*, resulting in a significant proportion ($> 11\%$) of the total solid disk mass remaining in an excited state, thus potentially acting as a source of material to explain the IR emission.
- Further modelling is required to understand whether dynamical models can naturally explain the origin of the parent bodies that cause the observed IR emission.

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