Aims/ To examine whether or not the inferred mutual inclinations of the Kepler multi-planet systems are consistent with a scenario in which the planets have undergone dynamical instabilities and giant impacts.

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Formation of Kepler compact multi-systems by dynamical instabilities and giant impacts

1/ Background

The Kepler multi-planet systems can provide templates for statistical studies of planetary system formation. Around 50% of these exoplanets appear to be in **multi planet systems**, and many of them are **closely packed**. The relative numbers of 2- to 7-planet systems discovered are dependent upon the **mutual planetary inclinations**. It is of interest to examine whether or not a planetary formation model based on dynamical instability and giant impacts can reproduce the statistics of the **observed relative transit multiplicity**. The spacings of the planets are typically ~ 20 mutual Hill radii, suggesting that such a scenario is possible.

2/ Methods

We use a selection of **Kepler 5-planet systems*** to provide templates for generating initial conditions for **N-body simulations** in which the planets grow through giant impacts.

- The 5 original Kepler planets are replaced by **20 protoplanets** with the same total mass
- We consider perfect hit-and-stick and imperfect (Leinhardt & Stewart 2012) accretion routines,
- We consider two sets of initial conditions with high and low values for the eccentricities (e) and inclinations: [e, I] = **[0.02, 0.01]** and **[0.002, 0.001]**.

The initial conditions represent the stage of the systems after gas disc dispersal, and when they contain numerous (20) protoplanets in a compact configuration, such that final assembly of the planets occurs through dynamical relaxation and giant impacts.

We performed synthetic transit observations of the resulting planetary systems from our N-body simulations, and compared them to the Kepler data.

* Selected systems in this study are Kepler-55, 80, 84, 102, 154, 169, 292, and 296.

3/ Results

3.1 Multiplicities and system parameters

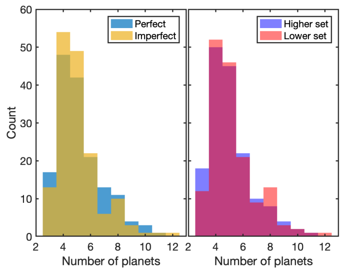

Figure 1. Multiplicity distribution from all simulations. The maximum multiplicity is 12, and no 1- or 2-planet systems are formed. Having 4 or 5 planets remain in the system is the most common outcome

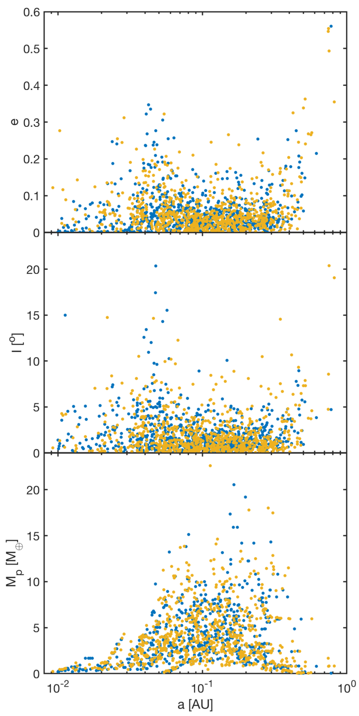

Figure 2. Comparison of e, I, and M_p with respect to a for perfect (blue point) and imperfect (yellow point) collision simulations. We can see the high values of e and I on the two edges of the simulations where collisions occurred less frequently.

3.2 Mutual separations: *K*-values

The K-value measures the separation between neighbouring planet pairs, in units of the mutual Hill radius, and relates to the long term stability of planetary systems (e.g. Pu & Wu 2015). The typically estimated K-values of Kepler multi-systems is ~20, consistent with the outcomes of our simulations.

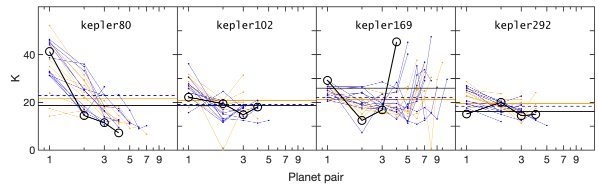

Figure 3. *K*-values of the planet pairs from the higher (orange points) and lower (blue points) e and I set. Estimates for the original Kepler systems shown by black circles.

3.3 Synthetic transit observations and multiplicity ratios

By knowing the final orbital parameters from the simulations, and the radius of the host star, we conducted **synthetic transit observations** of the planetary systems formed in the N-body systems. We then computed the ratio of the number of 2-transiting planet systems to the number of 1-transiting planet systems, and the number of 3-transiting planet systems to the number of 2-transiting plane systems etc, arising from the synthetic observations. We denote these ratios as follows (and display them in figure 4):

$$\text{Transit Ratio}(i,j) = \frac{\text{number of } i\text{–transiting systems}}{\text{number of } j\text{–transiting systems}}.$$

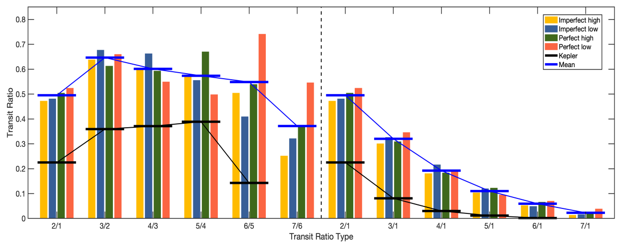

Figure 4. Synthetic transit ratios from all four sets of our simulations. The left panel shows the ratios of 2-planet to 1-planet systems, 3-planet to 2-planet systems, etc. The right panel shows the ratios of 2-planet to 1-planet systems, 3-planet to 1-planet systems, etc. We can see that all the N-body **simulations provided a higher Transit Ratio** than the *Kepler* observations, with the discrepancy being typically a factor of ~2.

4/ Conclusion

Overall, our study provides support for the idea that some *Kepler* multi-planet systems formed from a compact collection of protoplanets that underwent dynamical instabilities and giant impacts . The simulations produce masses, period ratios and mutual separations that are in good agreement with those inferred from the *Kepler* data. Using synthetic transit observations, we also test the idea that essentially all observed *Kepler* systems are multi-systems formed in this manner, with the range of observed multiplicities arising simply because of the mutual inclinations between the planets, where these inclinations occur as a result of dynamical scattering during formation. The synthetic transit observation results, however, are discrepant with the *Kepler* data, and produce, in a relative sense, too many high multiplicity systems. We conclude that either the formation scenario presented here applies only to a sub-set of the *Kepler* systems, or some other process not included in our simulations has increased the mutual inclinations of planets within the *Kepler* systems.

References

Leinhardt Z. M. & Stewart S. T., 2012, ApJ, 745, 79

Pu B. & Wu Y., 2015, ApJ, 807, 44