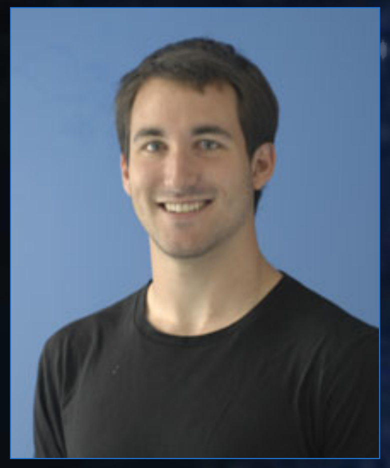
The Occurrence Rate of Hot Jupiters in the *Kepler* Field

Evan Sinukoff

Supervisor: Andrew Howard

Institute for Astronomy, University of Hawaii



Abstract

Using the latest *Kepler* data, we employ Bayesian statistical methods to measure an overall Hot Jupiter (HJ) occurrence rate of 5.8 ± 0.6 per thousand stars. We look for a deficit of HJs around cool stars with convective envelopes. Winn et al. (2010) suggest that HJs orbiting cool stars should be lost to tidal interactions with the stellar convective envelope. However, we find a slight decrease in occurrence rate around hotter stars, which have less massive convection zones. This suggests that orbital decay caused by tidal interactions with stellar convective envelopes does not typically lead to the destruction of HJs over stellar main sequence lifetimes.

Motivation

- Studying patterns of planet occurrence informs formation theories

Winn et al. (2010), Albrecht et al. (2012)

- Found hot Jupiter orbital plane is mostly misaligned with stellar spin axis for stars with $T_{eff} \gtrsim 6250$ K, corresponding to approximate temperature at which stellar convective envelope becomes insignificant

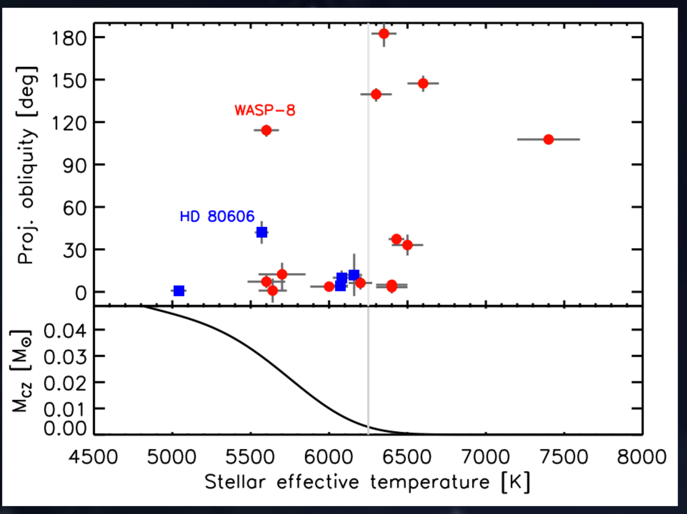


Figure 1: Winn et al. (2010). *Top*: Projected obliquity (spin-orbit angle) versus stellar T_{eff}. Red circles and blue squares indicate systems discovered by transit photometry and RV surveys respectively. Below ~6250 K, systems are mostly aligned, while systems above ~6250 K have a broad range of obliquities. Two well-understood exceptions are labeled. *Bottom*: Mass of convection zone versus T_{eff} for a main sequence star, from Pinsonneault, DePoy & Coffee (2001). Above ~6250 K, the convection zone has negligible mass suggesting a link between convective envelopes and hot Jupiter formation.

The Winn-Albrecht model – tidal damping

Hot Jupiter formation around all stars is dominated by scattering events and/or Kozai cycles (rather than disk migration). Initial systems would thus have a wide range of obliquities. For cooler stars, obliquities are then damped by tidal interactions between planet and stellar convective envelope over ~Gyr timescales. Minimal damping occurs for hot stars due to lack of convective envelope, preserving wide range of obliquities.

A potential shortcoming

Obliquity damping would be accompanied by orbital decay and engulfment of planet by star. Assuming that realignment timescales are similar to orbital decay timescales, Winn et al (2010) showed that engulfment is avoided only if envelope is decoupled from rest of star – an admittedly doubtful scenario. However, Lai (2012) argued that orbital decay timescales can be much longer than realignment timescales. If correct, hot Jupiters would survive tidal damping.

Testing the planet destruction hypothesis

If orbital decay occurs on a similar timescale as spin-orbit realignment, one would expect a spike in HJ occurrence for stars hotter than ~6250 K similar to that observed for stellar obliquities. Alternatively, a decay timescale longer than stellar main sequence lifetimes would not produce a discontinuity.

Testing this prediction requires a survey with complete HJ detection for a large sample of stellar targets with precise effective temperature measurements. *Kepler* is the only sufficient survey.

Methods

Dataset

- Consists of 144 983 *Kepler* targets, 85 planets from the latest *Kepler* data release (Batalha et al. 2012)

Selection Criteria	
Stellar Effective Temp. [K]	3600 - 7100
Stellar Log(g) [cgs]	4.0 - 4.9
Planet Radius [$R_\oplus$]	6 - 32
Orbital Period [days]	0.1 - 10

Bayesian Analysis

- Assume occurrence probability P_{HJ} is given by some function of stellar effective temperature with one or more free parameters

Model #	Assumed Functional Form of Occurrence Rate *	Purpose	Result
1	$P_{HJ} = C_0$	Measure overall occurrence rate	Fig. 2
2	$P_{HJ} = \begin{cases} C_0, & T_{eff} < 6250\text{ K} \\ C_0 + \delta_{6250}, & T_{eff} \geq 6250\text{ K} \end{cases}$	Test for discontinuity in occurrence rate at T_{eff} = 6250 K	Fig. 3
3	$P_{HJ} = \begin{cases} C_0, & T_{eff} < T_{transition} \\ C_0 + \delta, & T_{eff} \geq T_{transition} \end{cases}$	Test for discontinuity in occurrence rate at all T_{eff}	Fig. 4

*C_0, δ_{6250}, δ, $T_{transition}$ are free parameters

- Each unique set of free parameters constitutes a "model"
- Bayesian probability theory used to determine relative probability of different models

Probability *P* of model *M* given data *D*:

$$\mathrm{P}(M|D) \propto \mathrm{P}(D|M) \times \mathrm{P}(M) \quad (1)$$

Posterior probability — Likelihood function — Prior probability

We assume uniform priors and derive likelihood function L:

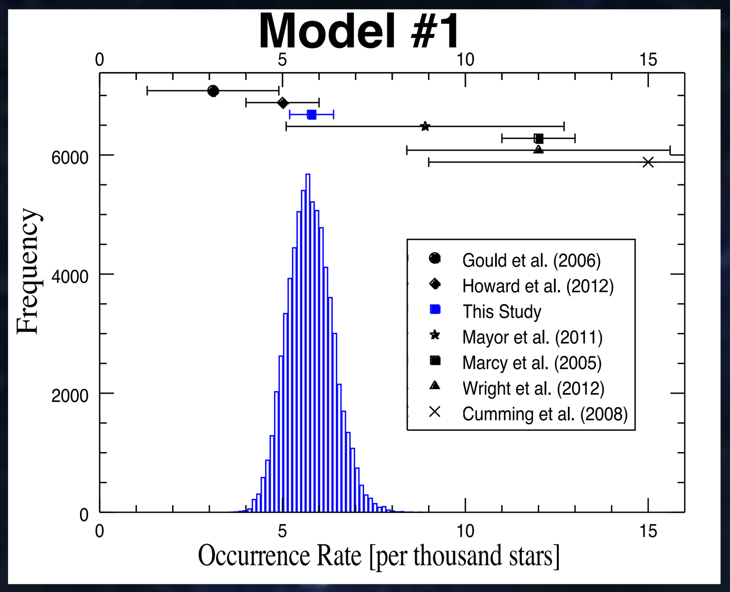
$$\log(L) = \sum_{\text{Detections}} \log(P_{HJ} P_{trans}) + \sum_{\text{Non-detections}} \log(1 - P_{HJ} P_{trans}) \quad (2)$$

P_{HJ} = Hot Jupiter occurrence rate, P_{trans} = Transit probability

- For non-detections, P_{trans} calculated by integrating over planet period distribution measured by Howard et al. (2012)
- Zero orbital eccentricity assumed
- T_{eff} taken from *Kepler Input Catalogue* (Brown et al. 2011)
- Markov Chain Monte Carlo (MCMC) program created in IDL to generate posterior probability distributions
- Each free parameter estimated as median of posterior probability distribution marginalized over all other parameters

Results

Overall HJ Occurrence Rate



Measured occurrence rate :

5.8 ± 0.6 [per thousand stars]

- Consistent with *Kepler* study by Howard et al. (2012)
- Difference between transit and RV survey results is of unknown origin
  - Binaries in *Kepler* field may dilute occurrence measurements
  - Different studies use slightly different selection criteria (e.g. Gould et al. (2006) use P < 5 d)

Figure 2: Overall occurrence rate posterior (blue histogram). Occurrence rates measured in this and other studies are represented by single points with 1-sigma error bars. Error bars for Gould et al. (2006) indicate a 90% confidence interval. Results of Gould et al. (2006) and Howard et al. (2012) are derived from *OGLE-III* and *Kepler* transit surveys respectively. All other studies use RV data.

Occurrence Rate vs T_{eff}

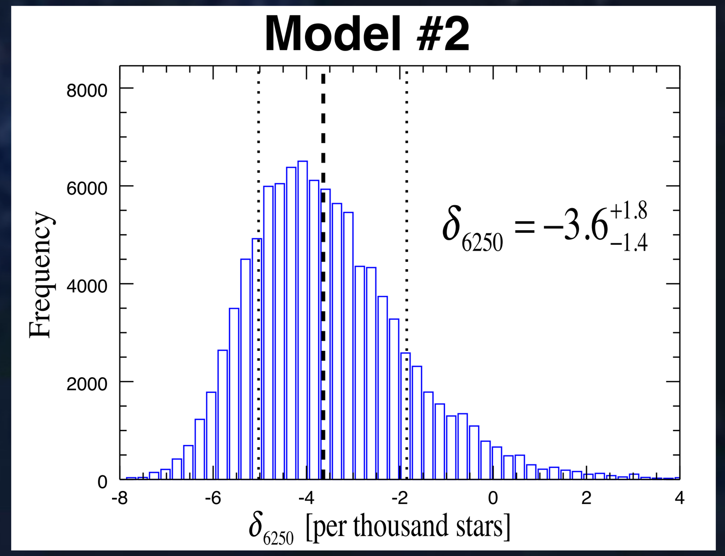


Figure 3: Posterior probability distribution of δ_{6250} derived from MCMC simulations. δ_{6250} represents the difference between the overall occurrence rate for stars hotter and cooler than 6250 K. A negative δ_{6250} indicates the occurrence rate is lower for stars hotter than 6250 K.

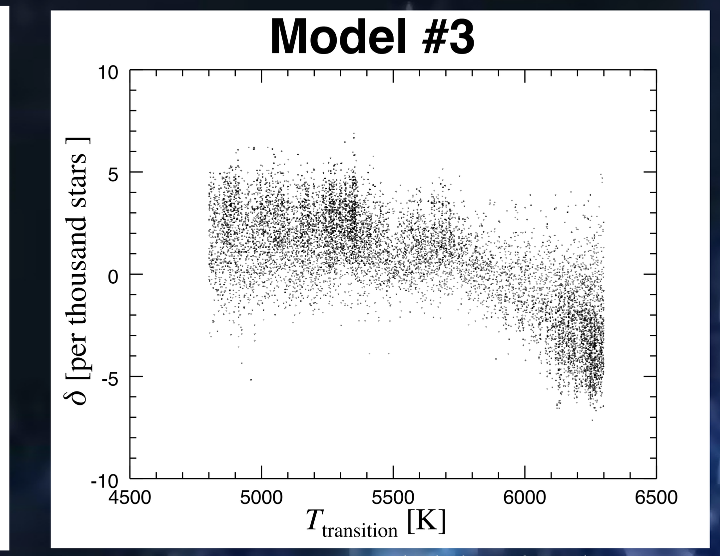


Figure 4: 2D posterior probability distribution (sampled 50 000 times) of the difference δ between overall occurrence rate for stars hotter and cooler than $T_{transition}$ as a function of $T_{transition}$. The decrease in δ with increasing temperature seen above ~5800 K indicates a decreasing occurrence rate with decreasing convective envelope mass. This is opposite of trend expected if tidal damping causes planet destruction.

- If planet tidal interaction with stellar convective layer causes destructive inward spiral, then one expects a deficiency of HJs around cooler stars
- Discontinuity at T_{eff} = 6250 K of $\delta_{6250} = -3.6^{+1.8}_{-1.4}$ per thousand (Fig. 3) suggests HJ occurrence rate decreases above 6250 K where convection zone mass becomes negligible
- Decrease in δ with increasing temperature seen above ~5800 K (Fig. 4) indicates a decreasing occurrence rate with decreasing convective envelope mass. This is inconsistent with HJ destruction via tidal damping.
- Suggests that tidal interactions between stellar convective envelope and HJs do not generally lead to HJ destruction over main sequence lifetime of star
- Supports Lai (2012) hypothesis that realignment of stellar spin and planet orbit occurs on shorter timescale than orbital decay
- These results are preliminary

Next Steps

- Investigate occurrence rate as function of orbital period
- Account for false positive rates
- Quantify statistical significance of results

References

- Albrecht, S., et al. 2012, ApJ , 757, 18
- Batalha, N. M., et al. 2012, arXiv:1202.5852
- Brown, T. M., et al. 2011, AJ, 142, 112
- Cumming, A., et al. 2008, PASP, 120, 531
- Gould, A., et al. 2006, Acta Astron. , 757, 18
- Howard, A. W., et al. 2012, ApJS, 201, 15
- Lai, D. 2012, MNRAS, 423, 486
- Marcy, G. W., et al. 2005, ApJ, 619, 570
- Mayor, M., et al. 2011, arXiv:1109.2497
- Pinsonneault, M.H., DePoy, D.L., & Coffee, M. 2001, ApJ, 556, L59
- Winn, J. N., et al. 2010, ApJ, 718, L145
- Wright, J. T., et al. 2012, ApJ, 753, 160