Architectural and Chemical Insights into the Origin of Hot Jupiters

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OHP 2015: Twenty years of giant exoplanets
6 October 2015
The Exoplanet Population

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How do these Hot Jupiters Form?

Disk-driven migration

Lin et al. (1996)
How do these Hot Jupiters Form?

Weidenschilling & Marzari (1996)

Rasio & Ford (1996)

Planet-planet scattering
How do these Hot Jupiters Form?

Kozai-Lidov migration

Holman et al. (1997)
Mazeh et al. (1997)
Kiseleva et al. (1998)
Fabrycky & Tremaine (2007)
How do these Hot Jupiters Form?

<table>
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Yes should be observed

No should not be observed
How do these Hot Jupiters Form?

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Yes should be observed

No should not be observed

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### How do these Hot Jupiters Form?

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- **Yes** should be observed
- **No** should not be observed
Some Lore: Hot Jupiters are Lonely

Wright et al. (2009)
Steffen et al. (2012)
Some Lore: Hot Jupiters are Lonely

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\[
P(GP | HJ) = ?
\]

Wright et al. (2009)
Steffen et al. (2012)

\[P(GP) = \text{Giant-planet probability}\]
\[P(HJ) = \text{Hot-Jupiter probability}\]
Bayes' Theorem

\[
P(GP | HJ) = \frac{P(HJ | GP) P(GP)}{P(HJ | GP) P(GP) + P(HJ | GP') P(GP')}
\]

- \( P(GP) \) = Giant-planet probability
- \( P(HJ) \) = Hot-Jupiter probability
Giant Planet Probability

Cumming et al. (2008)
Wright et al. (2012)

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Bayes' Theorem

\[ P(GP|HJ) = \frac{P(HJ|GP)P(GP)}{P(HJ|GP)P(GP) + P(HJ|GP')P(GP')} \]

\[ P(GP) = 0.084^{+0.01}_{-0.01} \text{ (e.g., Cumming et al. 2008)} \]
\[ P(HJ) = 0.012^{+0.004}_{-0.003} \text{ (e.g., Wright et al. 2012)} \]
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\[ P(GP') = 1 - P(GP) = 0.916^{+0.01}_{-0.01} \]
Multiple Giant Planet Systems

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Multiple Giant Planet Systems

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Period [days]
Bayes' Theorem

\[ P(GP|HJ) = \frac{P(HJ|GP)P(GP)}{P(HJ|GP)P(GP) + P(HJ|GP')P(GP')} \]

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\[ P(GP') = 1 - P(GP) \]

\[ = 0.916^{+0.01}_{-0.01} \]

\[ P(HJ|GP) = \frac{4}{139} \]

\[ = 0.027^{+0.02}_{-0.01} \]
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P(HJ|GP) = \frac{4}{139}
\]

\[
= 0.027^{+0.02}_{-0.01}
\]

\[
P(HJ|GP') = \frac{(10 - 3)}{\{836 [1 - P(GP)]\}}
\]

\[
= 0.0087^{+0.004}_{-0.003}
\]
Bayes' Theorem

\[ P(GP|HJ) = \frac{P(HJ|GP)P(GP)}{P(HJ|GP)P(GP) + P(HJ|GP')P(GP')} \]

\[ P(GP|HJ) = 0.22^{+0.1}_{-0.1} \]
Bayes' Theorem

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\[
P(GP|HJ) = 0.22^{+0.1}_{-0.1}
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\[
P(GP) = 0.084^{+0.01}_{-0.01}
\]

Cumming et al. (2008)
Any exterior giant planet
Companion Probability (inside $a_{\text{ice}}$)

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Companion Probability

Hot Jupiters are not lonely!

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**Yes** should be observed

**No** should not be observed

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$\Sigma_{\text{solids}} \propto \text{planet formation efficiency}$
\[ \Sigma_{\text{solids}} \propto \text{planet formation efficiency} \]
\[ \propto f_{\text{solids}} M_{\text{disk}} \]
\[ \text{g cm}^{-2} \]

fraction of mass that is in solid form (dust grains)
Planet Formation

\[ \Sigma_{\text{solids}} \propto \text{planet formation efficiency} \]

\[ \propto f_{\text{solids}} M_{\text{disk}} \]

\[ \propto Z M_\star \]

fraction of mass that is in solid form (dust grains)

mass fraction of metals

Gordon et al. (2003)
Andrews et al. (2013)
What About Other Elements?

The Bulk Earth Big Ten

O 32.4%  Fe 28.2%  Si 17.2%  Mg 15.9%  Ni 1.6%
Ca 1.6%  Al 1.5%  S 0.7%  Na 0.2%  Ti 0.1%

Allègre et al. (1995)
What About Other Elements?

The Bulk Earth Big Ten

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Brugamyer et al. (2011)
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*Yes should be observed*  

*No should not be observed*  

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Na 0.2% Dead zone is pushed out
Planet Formation

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Na 0.2%

Dead zone moves in
Logistic Regression

\[ P(Y) = \frac{1}{1 + e^{-(\beta_0 + \sum \beta_i x_i)}} \]
What About Other Elements?

The Best Model

- Fe: 28.2%
- Si: 17.2%
- Ca: 1.6%
- Na: 0.2%
What About Other Elements?

The Best Model

Fe 28.2%
Si 17.2%
Ca 1.6%
Na 0.2%
What About Other Elements?

The Best Long-Period Model

Fe
28.2%
What About Other Elements?

The Best Long-Period Model

Only giant planets with $P < 100$ days orbit low-sodium stars!

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These analyses support the disk-driven migration scenario.
What About Other Elements?

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