Are hot neptunes partially evaporated hot jupiters?

Nuno C. Santos¹
and
Gwenael Boué¹
Pedro Figueira¹
Alexandre Correia²

¹ Centro de Astrofísica, Universidade do Porto (Portugal)
² Dep. de Física, Universidade de Aveiro (Portugal)
Neptunes and super-Earths

~80 with mass below 20 $M_{\text{Earth}}$ known to date

Planet detections in HARPS and CORALIE samples

Mayor et al. (2011, this conference)
Hot-neptunes and super-earths: what is their origin and nature?

- Failed cores that migrated inwards (e.g. Ida & Lin 2004, Mordasini et al. 2009)
- In-situ formation by accretion of planetesimals (e.g. Brunini & Cionco 2005; Hansen 2009)
- Embryo formation in compact system and subsequent migration through scattering (e.g. Ida & Lin 2010)
- Tidal downsizing of migrating embryo (e.g. Nayakshin 2011)
- Evaporated hot-jupiters? (e.g. Baraffe et al. 2004)
Hints from the observations: the period distribution

Comparison of period distribution for planets with mass below 5 M\textsubscript{Jupiter} separated in two groups: mass above and below 2 M\textsubscript{Neptune} (35+116 planets, respectively)

Only “single” systems are considered (for P<10 days)

\[ P(\text{KS}) < 10^{-4} \]
In brief...

- Jovian period distribution has average value of 3.5-days (sigma=1.6-days)
- Neptune period distribution has average value of 5.2 days (sigma=2.7-days)
- Statistically significantly different period distributions
- Confirmed with Kepler observations (Latham et al. 2011)
- Previous studies have also shown that there seems to be a mass-period relation in giant transiting planets (e.g. Mazeh et al. 2005, Southworth et al. 2007, Davis et al. 2009, Benitez-Llambay et al. 2011)
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- Can evaporation of a Jupiter into a Neptune explain the observed difference?
The model: orbit evolution in a generic case where a planet is evaporating

- Define two parameters:
  - angle between star and direction of ejection ($\theta$)
  - opening angle of the ejection stream ($\phi$)

- Consider a given ejection velocity ($V_{\text{esc}}$): typical values are between 10-20 km/s (Murray-Clay et al. 2009)

- Assume circular orbit
\[ \dot{m} = -\frac{B(t)}{r^2}, \quad \kappa(t) = \eta(\varphi) \frac{B(t)}{m(t)} V_{\text{esc}}, \]

\[ \eta(\varphi) = \frac{\int_0^\varphi \cos \varphi' \sin \varphi' d\varphi'}{\int_0^\varphi \sin \varphi' d\varphi'} = \frac{1 + \cos \varphi}{2} = \cos^2 \frac{\varphi}{2}. \]

\[ \frac{1}{2} v^2 - \frac{\mu(t)}{r} = -\frac{\mu(t)}{2}. \]

\[ \frac{dv}{dt} = -\frac{\mu(t)}{r^3} r + \sin \theta \frac{\kappa(t)}{r^3} \mathbf{k} \times \mathbf{r}, \]

\[ \frac{d\mathbf{v}}{dt} = -\frac{\mu(t)}{r^3} \mathbf{r} + \frac{\kappa(t)}{r^3} \mathbf{k} \times \mathbf{r}, \]

\[ \mu(t) = G(m_\star + m(t)). \]

\[ B(t) = -a^2 \langle \dot{m} \rangle_M. \]

\[ \left\langle \frac{da}{dt} \right\rangle_M = -2\tau \frac{v_0}{v} \frac{\langle \dot{m} \rangle_M}{m} a. \]

\[ \left\langle \frac{da}{dt} \right\rangle_M = -\frac{a}{\mu} + 2 \frac{n \kappa \sin \theta}{\mu(1 - e^2)} a. \]

\[ P_{\text{Nep}} = \left( 1 - \tau \ln \frac{M_{\text{Jup}}}{M_{\text{Nep}}} \right)^{-3}. \]

\[ a = a_0 \left( 1 - \tau \ln \frac{m_0}{m} \right)^{-2}. \]

\[ \left\langle \frac{da}{dt} \right\rangle_M = -\frac{a}{\mu} + 2 \frac{n \kappa \sin \theta}{\mu} a. \]

A few equations later...

\[ \tau = \eta(\varphi) \sin \theta \frac{V_{\text{esc}}}{v_0}. \]

\[ P = P_0 \left( 1 - \tau \ln \frac{m_0}{m} \right)^{-3}. \]

\[ d^2 \frac{v_p}{dt^2} = -\frac{G m_\star m}{r^3} \mathbf{r} + \dot{m} V_{\text{str}}, \quad m \frac{dv_p}{dt} = \frac{G m_\star m}{r^3} \mathbf{r} + m V_{\text{str}}, \]

\[ m_* \frac{dv_*}{dt} = -\frac{G m_\star m}{r^3} \mathbf{r} + \dot{m} V_{\text{str}}, \]

\[ d^2 \frac{\mathbf{v}}{dt^2} = -\frac{G m_\star m}{r^3} \mathbf{r} + \dot{m} V_{\text{str}}, \]

\[ m \frac{dv}{dt} = \frac{G m_\star m}{r^3} \mathbf{r} + \dot{m} V_{\text{str}}, \]
Model results

It can be shown that under such conditions, the evolution of the orbit is given by:

\[
\frac{da}{dt} = -\frac{\dot{m}}{m_* + m} a - 2\tau \frac{v_0 \dot{m}}{v} m a,
\]

Where the “migration efficiency” parameter \( \tau \) is defined as:

\[
\tau = \cos^2 \frac{\phi}{2} \sin \theta \frac{V_{esc}}{v_0}.
\]

- If evaporation is isotropic (\( \phi=180^\circ \)) or radial (\( \theta=0^\circ \)), no migration occurs
- Maximum efficiency for collimated evaporation with \( \theta=90^\circ \)
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Maximum efficiency for collimated evaporation with $\theta=90^\circ$

The equation above implies that the initial and final periods of a neptune that is the result of an evaporated hot jupiter are related by:

\[
\frac{P_{\text{Nep}}}{P_{\text{Jup}}} = \left(1 - \tau \ln \frac{M_{\text{Jup}}}{M_{\text{Nep}}} \right)^{-3} ,
\]
Using the observed period distributions (assuming log-normal distributions) and the equation above, we can constrain the probability distribution function of $\tau$.
The distribution of $\tau$

PDF of $\tau$ in the $\theta$-$\varphi$ diagram assuming:

$V_{\text{esc}}=15$ km/s (intermediate value)

$v_0=145$ m/s ($P=3.2$ days)

$$\tau = \cos^2 \frac{\varphi}{2} \sin \theta \frac{V_{\text{esc}}}{v_0}.$$
The distribution of $\tau$

Estimated hot spot position of HD189733b
(Knutson et al. 2007)
Some remarks...

- The necessary evaporation properties may indeed exist in the real world:
  - Hot spots - not necessarily oriented towards the star - have been observed and predicted (Knutson et al. 2007, Showman et al. 2011)
  - Planets may have time to evaporate
    - If star is young (T Tauri), there may be enough radiation to explain the escape velocities needed (Ribas et al. 2005, Murray-Clay et al. 2009)
    - If the planet is young (bloated) evaporation times may be short enough! (Mordasini et al. 2009, Erkaev et al. 2007)
Conclusions

- We present a model that explains the formation of hot-neptunes as evaporated hot-jupiters.
- Model naturally explains the different observed period distributions.
- Model is time-independent: only depends on total ejected mass and on the geometry of the ejection.
Thank you!

For details: Boué et al. 2011 (today in astro-ph)