Giant Planets in Open Clusters

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Open clusters are nature’s laboratories

- OCs have long been crucial for testing stellar evolution
- For given age, composition, dynamical environment, can characterize – as function of stellar mass – stellar structure, activity, binary population, etc.

How is planetary formation and evolution affected? What can we learn from comparative studies?
But are there any cluster planets to study?

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Year</th>
<th>Authors</th>
<th>Method</th>
<th>Short period planets*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyades</td>
<td>2004</td>
<td>Paulson+</td>
<td>RV</td>
<td>0</td>
</tr>
<tr>
<td>NGC 7789</td>
<td>2005</td>
<td>Bramich+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>NGC 2158</td>
<td>2006</td>
<td>Mochejska+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>NGC 7086</td>
<td>2006</td>
<td>Rosvick+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>NGC 6791</td>
<td>2007</td>
<td>Montalto+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>NGC 188</td>
<td>2008</td>
<td>Mochejska+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>Praesepe</td>
<td>2008</td>
<td>Pepper+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>NGC 2362</td>
<td>2008</td>
<td>Miller+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>M37</td>
<td>2009</td>
<td>Hartman+</td>
<td>Transit</td>
<td>0</td>
</tr>
<tr>
<td>M67</td>
<td>2012</td>
<td>Pasquini+</td>
<td>RV</td>
<td>0</td>
</tr>
</tbody>
</table>

*2 long period super-Jupiters were known to orbit massive evolved stars in the Hyades (Sato+ 2007) and NGC 2423 (Lovis & Mayor 2007).
Where are the cluster hot Jupiters?

Planets are common around field stars (Fressin+ 2013, Mayor+ 2011). Most stars form in a clustered environment (Lada² 2003, Bressert+ 2010). Shouldn’t we expect planets in clusters?

Potential explanations:

1. Dense stellar environments (like those that survive as clusters) inhibit the formation and/or migration of giant planets. (e.g., Eisner+ 2008).

2. Given hot Jupiter occurrence around field stars (~1%; Mayor+ 2011, Wright+ 2012), all previous surveys combined might only expect 1 (or 0) planets (van Saders & Gaudi 2011).

But #1 is an important point to keep in mind! We KNOW the stellar environment affects planets at some level. Is this a smooth function of environment? Is there a threshold?
More recent history of cluster planets

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</thead>
<tbody>
<tr>
<td>Praesepe</td>
<td>2012</td>
<td>Quinn+</td>
<td>RV</td>
<td>2</td>
</tr>
<tr>
<td>NGC 6811</td>
<td>2013</td>
<td>Meibom+</td>
<td>Transit</td>
<td>2 (mini-Neptunes)</td>
</tr>
<tr>
<td>Hyades</td>
<td>2014</td>
<td>Quinn+</td>
<td>RV</td>
<td>1</td>
</tr>
<tr>
<td>M67</td>
<td>2014</td>
<td>Brucalassi+</td>
<td>RV</td>
<td>2</td>
</tr>
</tbody>
</table>

Adjusted for completeness:

Field stars: $\sim 1\%$

Praesepe and Hyades: $1.97^{+1.92\%}_{-1.07\%}$

[Fe/H]=0 equivalent: $0.99^{+0.96\%}_{-0.54\%}$

M67: $2.00^{+3.00\%}_{-1.50\%}$

NGC 6811: consistent
Example experiment: Does hot Jupiter migration occur primarily through interactions with the disk (Type II) or with other bodies (planet-planet scattering, Kozai-Lidov)?

Type II
- Expected to preserve circular orbits
- Occurs within 10 Myr

Planet-planet scattering
- Can produce significant eccentricity
- May take hundreds of Myr

Observing soon after migration can identify dominant mechanism
Case Study: HD 285507b

Eccentricity could be indicative of:
- the mode of migration
- ongoing dynamical interaction
- a recent encounter

Hyades $t_{\text{age}} = 625$ Myr

Circularization timescale is roughly:

$$t_{\text{cir}} = 1.6 \text{ Gyr} \times \left( \frac{Q_P}{10^6} \right) \times \left( \frac{M_P}{M_{\text{Jup}}} \right) \times \left( \frac{M_*}{M_{\text{Sun}}} \right)^{-1.5} \times \left( \frac{R_P}{R_J} \right)^{-5} \times \left( \frac{a}{0.05 \text{ AU}} \right)^{6.5} \approx 11.8 \text{ Gyr}$$

(Adams & Laughlin 2006)

We call HD 285507b “dynamically young” ($t_{\text{age}} < t_{\text{cir}}$); it may have migrated via planet-planet scattering or Kozai cycles
Dynamically young hot Jupiters are eccentric.

K-S test: samples come from different parent distributions with 99.997% confidence.
A constraint on the tidal quality factor $Q_P$

- Changing $Q_P$ changes the two samples
- A K-S test for each new $Q_P$ quantifies the difference
- The most significant difference should occur for the true $Q_P$ value – that is, when we have divided the dynamically young and old samples in the correct place
A constraint on the tidal quality factor $Q_p$

![Graph showing the KS Probability vs. $Q_p$]

- Jupiter-Io constraint (Yoder & Peale 1981)
- $\log Q_p = 6.14^{+0.41}_{-0.25}$ (Quinn et al. 2014)

The graph illustrates the distribution of probabilities for $Q_p$, with the highlighted region showing the constrained values based on the Jupiter-Io and Quinn et al. 2014 constraints.
Younger planets constrain migration via required timescale
- Hot Jupiters orbiting T Tauri stars would prove Type II can work
- Hot Jupiter frequency should change with age, dependent upon the importance of each mechanism

PTFO 8-85961 is a candidate hot Jupiter orbiting a T Tauri star (van Eyken+ 2012, Barnes+ 2013), though it has been called into question with further observation (Yu+ 2015).
Presence of long period giant planets can:
- Provide “smoking gun” evidence for migration of an inner planet.

A system of 44-day and 500(?)-day massive planets in Coma Berenices.

A 90-day Jupiter with an outer companion (likely stellar), in Coma Ber.
Presence of long period giant planets can:

- Map planetary system structure as a function of environment

Orbits (and survival) of terrestrial planets are shaped by their giant counterparts. Do long-period Jupiters also have occurrence at similar rates in clusters and the field?
Presence of long period giant planets can:

- Directly connect RV and directly imaged populations

Adolescent OCs are a sweet spot for RVs + direct imaging.

Very young stars rotate too rapidly with too much activity for RVs.

Older substellar companions are hard to directly image.

This allows characterization of substellar companions at all separations around a single population of well-characterized stars.
Summary: OCs as Exoplanet Laboratories

- Controlled for age, composition, dynamical environment
  - planet-stellar mass dependence, planet-metallicity dependence, etc.
- Occurrence and orbits as function of age constrain migration
  - plus, additional benefits like the constraint on $Q_p$
- Benchmark transiting systems (precise stellar and planetary properties)
- Direct imaging of wide giants/brown dwarfs for formation/evolution
  - well-characterized stars, especially age, enable better model comparison
- Observationally connect populations of wide imaged companions and RV planets
- With K2 and TESS, the OC opportunity extends to small planets
- OCs represent limits on the environmental influence on planet formation – do architectures of planetary systems (including small planets!) change in the densest stellar environments?
- And more!