Discoveries of Young Planets Constrain Theories of Formation and Migration

Russel White - Georgia State University

Image credit: NASA
20+ Years of Exoplanet Science…

1892 confirmed exoplanets
4696 candidates (Kepler)
~1/3 in multi-planets systems
NASA exoplanet archive

One in five stars has Earth-sized planet in the Habitable zone (Kepler)

Many short-period gas giant planets
... the hot Jupiters
(1.2 ± 0.4% with P < 10 d; M > 0.5 M_{Jupiter})
(Wright et al. 2012)
How Do Gas Giant Planets Form?

(1) Initiated by core accretion?
- slow (few Myr) assembly
  - e.g. Mizuno 1980; Pollack et al. 1996

(2) Gravitational Instabilities?
- quick (< 1 Myr) collapse; hotter, larger planets
  - e.g. Mayer et al. 2002; Boss 2003

Marley et al. 2007; Fortney et al. 2008
Some Must Migrate Inward. How?

(1) planet - disk?
likely damp eccentricities;
occur within 10 Myr
(e.g. Goldreich & Tremaine 1980)

(2) planet – planet, Kozai
likely excite eccentricities;
may take 100s Myr years
(see Winn & Fabrycky 2015)

Dynamical may be erased by tidal circularization (> 1 Gyr).
Need to Find Young Planets

Requires looking around young stars

Age would constrain formation, migration timescale (resolve mass/age ambiguity)

Eccentricities would constrain migration process

Image credit: NASA
Nearby directly imaged *young planets* … maybe

Locations of parent stars

HR 8799, A5/F0

κ Andromeda, B9

October 30, 2012
Keck/NIRC2 Lp

20 AU
0.5"

Marois et al. (2008, 2012)

e.g. Carson et al. (2012)
What’s a planet?

**IAU Definition**
1. Orbits the Sun
2. Round
3. Cleared its orbital path

Pluto is a dwarf planet

**Astronomer’s Convention**

1. A low mass object that orbits a star (or brown dwarf) and …
   - OR -

   Has a mass less than $\sim 13 \, M_{\text{Jup}}$ (doesn’t fuse $^2\text{H}$)

   Formed out of a disk around that star
Masses for directly imaged planets come from model comparisons at an assumed age.
Nearby directly imaged young planets … maybe

HR 8799: companions are planets if younger than 100 Myr (e.g. Carson et al. 2012)

κ Andromeda: companions are planets if system is younger than ~35 Myr

Other intermediate mass star planet hosts include β Pic, Fomalhaut, HD 95086
List of directly imaged “Planets”

Planets masses are based on the predictions of evolutionary models, assuming an age

<table>
<thead>
<tr>
<th>Star</th>
<th>SpT</th>
<th>Planet</th>
<th>D (pc)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappa And</td>
<td>B9</td>
<td>b</td>
<td>52</td>
<td>2012</td>
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<tr>
<td>Fomalhaut</td>
<td>A3</td>
<td>b</td>
<td>7.6</td>
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<td>Beta Pic</td>
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<td>b</td>
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<td>2008</td>
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<td>HD95086</td>
<td>A8</td>
<td>b</td>
<td>90</td>
<td>2013</td>
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<tr>
<td>HR 8799</td>
<td>A5/F0</td>
<td>bcde</td>
<td>39</td>
<td>2008</td>
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<tr>
<td>GJ 504</td>
<td>G0</td>
<td>b</td>
<td>18</td>
<td>2013</td>
</tr>
<tr>
<td>LkCa 15</td>
<td>K5</td>
<td>b</td>
<td>145</td>
<td>2011</td>
</tr>
<tr>
<td>1RXS 1609</td>
<td>K7</td>
<td>b</td>
<td>145</td>
<td>2008</td>
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<tr>
<td>ROXs 42B</td>
<td>M0</td>
<td>b</td>
<td>135</td>
<td>2014</td>
</tr>
<tr>
<td>Ross 458 AB</td>
<td>M0.5/M7</td>
<td>b</td>
<td>11.4</td>
<td>2011</td>
</tr>
<tr>
<td>FW Tau AB</td>
<td>M5</td>
<td>b</td>
<td>145</td>
<td>2014</td>
</tr>
<tr>
<td>2M1207</td>
<td>M8</td>
<td>b</td>
<td>53</td>
<td>2004</td>
</tr>
</tbody>
</table>

Nearby “A type” stars
10s – 100s Myr

More Distant T Tauri stars
Intermediate mass stars swell as they age. Size measurements could allow more accurate model comparisons.
The CHARA Array
Georgia State University
(PI: Hal McAlister)

331 meters
What does an interferometer ‘see’?
What does an interferometer ‘see’?

When the pathlengths are the same, **constructive** and **destructive** interference of light.
What does an interferometer ‘see’?

Measure the fringe contrast, or visibility

\[ V = \frac{I^+ - I^-}{I^+ + I^-} \]
For small stars ($\theta < 0.25$ mas), fringe contrast will be high.
For large stars (θ ~ 0.5-3.0 mas), fringe contrast will be small.
Why is This?

Parts of star interfere at different path lengths
Fringe contrast, or visibility $= 2[J_1(\pi \theta b / \lambda)]/(\pi \theta b / \lambda)$

longer baselines, shorter $\lambda = $ better resolution
$\theta = 0.342 \pm 0.008$ mas
(2% precision!)
With an accurate luminosity, can get an accurate temperature too (\( L = 4\pi R^2 \sigma T^4 \))

\[
R = 1.44 \pm 0.06 \, R_{\odot}, \quad T = 7193 \pm 87 \, \text{K}
\]

Age:
- 33 Myr if contracting,
- 90 Myr if expanding

Companions are planets!

Baines, White, Jones et al. 2012
But not as easy for many A stars because of their rapid rotation
(For example, Kappa And has a \( \text{vsini} = 176 \text{ km/s} \))

The rapidly rotating star Regulus, imaged with the CHARA Array (Monnier et al. 2007) shows “gravity darkening”.

Radius, temperature, and luminosity are all orientation dependent!
Ph.D. work of Mr. Jeremy Jones (GSU): Ages of all nearby northern, single A stars.

Measure oblateness, adopt a gravity law, and model visibilities (results for Megrez = δ UMa)

(Positional)
Ages ~ 10%
Masses ~ 5%
Ph.D. work of Mr. Jeremy Jones (GSU): Ages of all nearby northern, single A stars.

Measure oblateness, adopt a gravity law, and model visibilities (results for Megrez = δ UMa)

\[ T_{\text{pole}} = 9684 \text{ K} \]
\[ T_{\text{eq}} = 8413 \text{ K} \]
\[ R_{\text{pole}} = 2.00 \, R_{\odot} \]
\[ R_{\text{eq}} = 2.26 \, R_{\odot} \]

(Positional)
Ages
\(~ 10\%\)
Masses
\(~ 5\%\)
Ph.D. work of Mr. Jeremy Jones (GSU):
Ages of all nearby northern, single A stars.

Based on MESA evolutionary models

A test of the technique:
Members of the Ursa Majoris Moving Group should be coeval

Jones, White et al. 2015
κ Andromeda

Is companion a planet (Carson et al. 2012) or a brown dwarf (Hinkley et al. 2014)?

At \( \sim 54 \) Myr, companion is a very low mass brown dwarf (15 \( M_{\text{Jup}} \))

Jones, White et al. in prep.
Need to Identify Young Planets

\[
\text{Age would constrain formation, migration timescale (resolve mass/age ambiguity)}
\]

\[
\text{Eccentricities would constrain migration process}
\]
Young Stars Are Typically Avoided in Radial Velocity (RV) Surveys

- Young stars are visibly fainter
  (the Sun was only 4400 K at 2 Myr, vs 5800 K today)
- More rapidly rotating
- Spots cause optical RV "noise"  (many 100 m/s)
  (Paulson & Yelda 2006; Heurta et al. 2007; Huelamo et al. 2008)
Spots can cause apparent RV shifts

The line bisector can reveal this artificial signal

from Queloz et al. (2001), using optical spectra
Advantage of Infrared Spectra

- Cool stars are relatively brighter
- Reduced spot contrast should reduce RV noise

![Graph showing intensity vs wavelength for different temperatures](image)

Optical  Infrared
RV Programs to Find Young Planets

- John Bailey (former UAH undergrad, now at Mich.)
- Justin Cantrell (GSU staff/grad.)
  - T Tauri age stars (1-20 Myr) infrared
- Nicole Cabrera (GSU; NSF Grad Fellow)
- Cassy Davison (GSU; former NSF Grad Fellow)
  - Adolescent age stars (10 – 150 Myr) Infrared & optical
- Sam Quinn (GSU; NSF Grad Fellow)
  - Open cluster stars (60 – 600 Myr) optical
First results in Bailey et al. 2012
20 stars in TWA, $\beta$ Pic (8-20 Myr)

using NIRSPEC at the Keck Observatory

Yields $\sim$50 m/s precision
Observed Dispersions: increase with vsini
outliers may have companions

- TWA 23
- GJ 3305
- TWA 13A

AO companion, now a new SB

New SB
TWA 23 has a companion, but companion is a star

Impressive RV curve for vsini = 22 km/s!
Does TWA 13A Harbor a Young Hot Jupiter?

$M \sim 2 M_{\text{jup}}$ with $P = 5.9$ d could fit data …
How much stellar “jitter” is there?

\[
\sigma^2_{\text{jitter}} = \sigma^2_{\text{obs}} - \sigma^2_{\text{instrumental}} - \sigma^2_{\text{photon}}
\]

(e.g. Butler et al. 1996)

- ~100 m/s
  (for vsini < 10 km/s)
- saturates at 180 m/s?
- Improvement over optical by 2-5 x!

(comparing to Paulson & Yelda 2006)
Companion Detection Limits

Monte Carlo Simulations

- circular 3 and 30 day orbits
- random inclinations

\[
< M_{\text{limit}} (3d) > = 8 \ M_{\text{jupiter}}
\]
\[
< M_{\text{limit}} (30d) > = 17 \ M_{\text{jupiter}}
\]

*No hot or warm massive planets!*

For AU Mic (assuming edge-on orbit):

\[
< M_{\text{limit}} (3d) > = 1.8 \ M_{\text{jupiter}}
\]
\[
< M_{\text{limit}} (30d) > = 3.9 \ M_{\text{jupiter}}
\]

*No hot or or warm Jupiters!*
Finding **Very** Young (short-period) Planets Will be Hard

See also Plavchan et al. 2013; Crockett et al. 2012; van Eyken et al. 2012

Why not search in open clusters?

Ages of 10s – 100s Myr; properties well established
A brief history of cluster planet searches

<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>
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<tr>
<td>NGC 7789</td>
<td>2005</td>
<td>Bramich+</td>
<td>Transit</td>
<td>0</td>
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<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>
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<tr>
<td>Praesepe</td>
<td>2008</td>
<td>Pepper+</td>
<td>Transit</td>
<td>0</td>
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<tr>
<td>NGC 2362</td>
<td>2008</td>
<td>Miller+</td>
<td>Transit</td>
<td>0</td>
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<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 are known to orbit massive evolved stars in the Hyades (Sato+ 2007) and NGC 2423 (Lovis & Mayor 2007).

Unlucky, or do clusters inhibit formation/migration?
A Search for Planets in Praesepe

Ph.D. thesis work of Mr. Sam Quinn
With Dr. David Latham, Guillermo Torres (SAO)

Observed 53 FGK Praesepe members with TRES (optical; ~10 m/s precision)

60” Tillinghast Reflector, Fred L. Whipple Observatory, Mt Hopkins, AZ
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60” Tillinghast Reflector, Fred L. Whipple Observatory, Mt Hopkins, AZ
The Praesepe Planets

\[ M \sin(i) = 0.540 \pm 0.039 \, M_J \]
\[ P = 4.4264 \pm 0.0070 \, \text{days} \]
\[ M_* = 1.234 \pm 0.034 \, M_\odot \]
\[ R_* = 1.167 \pm 0.121 \, R_\odot \]

\[ M \sin(i) = 1.844 \pm 0.064 \, M_J \]
\[ P = 2.1451 \pm 0.0012 \, \text{days} \]
\[ M_* = 0.952 \pm 0.040 \, M_\odot \]
\[ R_* = 0.868 \pm 0.078 \, R_\odot \]
No correlation with line bisector or chromospheric activity tracer
NASA Press Release:

Two ‘b’s in the Beehive

Image by R. Hurt
Gas giants exist in clusters; migration occurs within 600 Myr.
No constraints on migration mechanism

Tidal circularization timescale < Age of Cluster

We need to find more planets!

Project is now targeting 5 nearest open clusters:

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Dist. (pc)</th>
<th>Age (Myr)</th>
<th>[Fe/H] (dex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Praesepe</td>
<td>182</td>
<td>580</td>
<td>+0.19</td>
</tr>
<tr>
<td>Hyades</td>
<td>46</td>
<td>625</td>
<td>+0.13</td>
</tr>
<tr>
<td>Coma Ber.</td>
<td>87</td>
<td>450</td>
<td>-0.06</td>
</tr>
<tr>
<td>Pleiades</td>
<td>120</td>
<td>110</td>
<td>+0.03</td>
</tr>
<tr>
<td>α Persei</td>
<td>172</td>
<td>60</td>
<td>+0.00</td>
</tr>
</tbody>
</table>
The First Hyades hot Jupiter
Quinn et al. (2014)

HD 285507b

Radial Velocity (m s\(^{-1}\))

Orbital Phase

O-C

Normalized Flux

\[ M_p \sin(i) = 0.92 \, M_J \quad P = 6.09 \, \text{d} \]

Transits are ruled out
HD 285507b is Slightly Eccentric

Eccentricity could be a remnant of the migration process if it hasn’t yet tidally circularized

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

HD 285507b circularization timescale:

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

(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
A two planet system in Praesepe? (Did c cause the migration of b?)

Pr0211b

Pr0211c
A Warm Jupiter in Coma Berenices

\[ P = 44 \text{ d} \]
\[ M = 3 M_{\text{Jup}} \]

... and a longer term trend
The Pleiades: stellar activity or planets? (120 Myr)

\[ P = 2.23 \text{ days} \]
\[ e = 0.376 \]
\[ M_p \sin(i) = 0.56 M_J \]

\[ \Delta T = 93 \text{ days} \]
\[ N = 20 \]

\[ \Delta T = 35 \text{ days} \]
\[ N = 15 \]
John ("Jeb") Bailey PhD Thesis

... a more efficient way to survey open clusters for planets

Helped build M2FS, a multiple fiber-fed high-dispersion spectrograph for the 6.5-m Magellan Telescope (Las Campanas, Chile)

Details in Bailey, Mateo, White et al. 2015, submitted

A candidate planet in NGC 2422 at 135 ±15 Myr
Summary

Infrared RVs are still maturing (techniques/instruments) - likely offer the best chance of finding the *youngest* planets

Planets exists in open clusters - hot Jupiter frequency $= 1.97^{+1.92}_{-1.07}$%
- dynamical interaction influence migration
- on-going surveys will identify the first *transiting* hot Jupiter with precise age!