Sourav Chatterjee
Eric B. Ford
Frederic A. Rasio
WHAT DO WE KNOW ABOUT PLANETS IN STAR CLUSTERS?

- Few observed planets in star clusters
  - Planet around giant ε Tauri in Hyades (Bunéi et al. 2007)
  - Null results in 47tuc (Gilliland et al. 2000, Weldrake et al. 2005)
  - Pulsar planets in M4 (e.g., Backer 1993; Thorsett et al. 1999)

- Possible explanations
  - Metallicity vs planet-occurrence correlation
  - Stellar dynamics
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Possible explanations
- Metallicity vs planet-occurrence correlation
- Stellar dynamics

Do planets form around cluster stars at the same rate as they do around field stars?
OPEN STAR CLUSTERS IN KEPLER FIELD

Courtesy: kepler.nasa.gov
OPEN STAR CLUSTERS IN KEPLER FIELD

NGC6811
NGC6819
NGC6791
NGC6866

Courtesy: kepler.nasa.gov

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OPEN STAR CLUSTERS IN KEPLER FIELD

Courtesy: kepler.nasa.gov
Open Cluster NGC6791 in Kepler Field of View

- Super-Solar metallicity: Fe/H = 0.3
- High stellar number
- Low-density compared to typical GGCs
- In the field of view of Kepler

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical GC</th>
<th>NGC6791</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($M_\odot$)</td>
<td>$1 \times 10^5$</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Central Density ($M_\odot pc^{-3}$)</td>
<td>$1 \times 10^4$</td>
<td>30</td>
</tr>
</tbody>
</table>

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**Method**

Hénon-type Monte Carlo Cluster Evolution Code

- Modeling star clusters using a Hénon-type Monte Carlo code “CMC”
  - Two-body relaxation (Joshi, Rasio, & Portegies Zwart 2000)
  - Single and binary stellar evolution (Chatterjee et al. 2010)
  - Strong interactions including physical collisions and binary mediated interactions (Fregeau & Rasio 2007)
  - Galactic tidal stripping (Joshi, Nave, & Rasio 2001; recently updated in Chatterjee et al. 2010)
  - Large ranges of initial mass, compactness ($w_0$), initial binary fraction ($f_b$) are explored
  - A typical Galactic GC

NGC6791: Open cluster in the Kepler field of view
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- **A typical Galactic GC**
- **NGC6791: Open cluster in the Kepler field of view**
THE BEST-FIT MODEL OF NGC6791

Best fit parameters out of ~200 models:

- $N_i = 5 \times 10^4$
- $w_0 = 5$
- $r_v = 8$ pc
- $R_g = 10$ Kpc
- $f_b = 0.1$
- $f_p = 0.33$

(Platais et al. 2011)
Semimajor axis distribution is mostly unchanged even for $a \sim 100$ AU.
- \( \sim 7\% \) of large-\( a \) orbits acquire non-zero \( e \)
- Disturbed systems may create exotic planets
- Outer planet mediated indirect instability of close-in planets is rare
SYNTHETIC CMD FOR NGC6791

Main Sequence
SYNTHETIC CMD FOR NGC6791

Main Sequence

Giant Branch
SYNTHETIC CMD FOR NGC6791

Giant Branch

Main Sequence

Best chance to discover planets using Kepler
Detectable Planets (SNR>7)

$n_p$ vs $K_p$

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\textit{Detectable Planets (SNR>7)}

\[ n_p \text{ vs } K_p \]

- \(~10\) detections within a year of data collection
- Faint stars should not be neglected \((16.5 < K_p < 20)\)
- Kepler could be the first to discover \textit{planets around normal MS cluster stars}
Detectable Planets (SNR>7)

$n_p$ vs $R_p$

- $n_p$ (number of detectable planets)
- $R_p$ (planet radius in $R_\oplus$)

- Waveform data taken from

- Green line represents a threshold

- Graph shows distribution of detectable planets over time (1 yr, 3.5 yr, 8 yr)

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**Can Planets be Exchanged into Circumbinary Orbits?**

(Fregeau, Chatterjee, & Rasio 2006)
CAN PLANETS BE EXCHANGED INTO CIRCUMBINARY ORBITS?

![Graph showing the relationship between orbital distance (a) and velocity (v) for different cluster types.]

- **Resonant-type:** Planet Ejected [S, P]B → [B, S]P

(Fregeau, Chatterjee, & Rasio 2006)
Can Planets be Exchanged into Circumbinary Orbits?

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Can Planets be Exchanged into Circumbinary Orbits?

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Can planets be exchanged into circumbinary orbits?
Can Planets be Exchanged into Circumbinary Orbits?

Ionization:
Planet binary disrupted
[S, P]B → B, S, P

(Fregeau, Chatterjee, & Rasio 2006)
Ionization: Planet binary disrupted

$[S, P]B \rightarrow B, S, P$

(Fregeau, Chatterjee, & Rasio 2006)
CAN PLANETS BE EXCHANGED INTO CIRCUMBINARY ORBITS?

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Can Planets Be Exchanged into Circumbinary Orbits?

(Fregeau, Chatterjee, & Rasio 2006)
CONCLUSIONS

• Stellar dynamics has little effect on close-in planetary orbits

• Kepler should be able to discover planets in NGC6791

• Fainter stars (16.5 < K_p < 20) should not be neglected

• One year of observation may find ~10 giant planets (R_p > 10 R_⊕; exact number depends on initial assumptions)

• Kepler may well answer *whether planets form around cluster stars in a similar way as they do around field stars*

• Occassionally circumbinary planets may be created in cluster environments
  • Planet forms around a single star
  • Interaction with a stellar binary
  • Forms circumbinary planet
Planetary Orbit Initial Conditions

• a-distribution: Flat in logarithmic intervals between $10^{-2} - 10^{2}$ AU

• e-distribution: Circular

• M-distribution: Power-law, $df/d\log M \sim M^{-0.48}$ (Howard et al. 2011)

• $M_p$ is between $1 M_\oplus - 5 M_j$

• Planet’s radius $R_p = \min ( M_p^{2.06}, M_j )$

• $1/3$ of all stars have a planet
### A Typical Galactic Globular Cluster

<table>
<thead>
<tr>
<th>Property</th>
<th>Typical GC</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($M_\odot$)</td>
<td>$1 \times 10^5$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>Central Density ($M_\odot pc^{-3}$)</td>
<td>$1 \times 10^4$</td>
<td>$4 \times 10^4$</td>
</tr>
</tbody>
</table>
Effects of Stellar Dynamics on Planetary Orbits

Planets interior to 10 AU are undisturbed even for globular clusters
Radial Distribution of Detectable Planets

(Platais et al. 2011)
CALCULATION OF SNR FOR KEPLER DETECTABILITY

- Stellar L and R are obtained from CMC.
- L is converted first to B and V magnitudes using Lejunne spectra. \(K_p\) is then calculated using B and V assuming 4 Kpc distance.
- Planet’s M and a are obtained from CMC.
- Planet’s R is calculated using \(R_p = \min(M_p^{2.06}, M_J)\).
- For a given \(K_p\) CDPP is calculated using a polynomial fit of Kepler’s magnitude-dependent CDPP values (Gilliland et al. 2011).

\[
SNR = \left( \frac{R_p}{R_*} \right)^2 \sqrt{\frac{n_{tr} \cdot t_{dur}}{6.5 hr}}
\]

(e.g., Howard et al. 2011)
### Modeling NGC6791

**Explored initial conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stars</td>
<td>$10^4 - 10^5$</td>
</tr>
<tr>
<td>Concentration $w_0$</td>
<td>3 - 6</td>
</tr>
<tr>
<td>Virial Radius (pc)</td>
<td>3 - 8</td>
</tr>
<tr>
<td>Galacto-centric distance (Kpc)</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Stellar binary fraction ($f_b$)</td>
<td>0.1 - 0.5</td>
</tr>
<tr>
<td>Fraction of planet hosts ($f_p$)</td>
<td>0.33</td>
</tr>
</tbody>
</table>
# Initial Conditions for GC Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stars</td>
<td>$6 \times 10^5$</td>
</tr>
<tr>
<td>Concentration $w_0$</td>
<td>6</td>
</tr>
<tr>
<td>Virial Radius (pc)</td>
<td>4</td>
</tr>
<tr>
<td>Galacto-centric distance (Kpc)</td>
<td>8.5</td>
</tr>
<tr>
<td>Stellar binary fraction ($f_b$)</td>
<td>0.1</td>
</tr>
<tr>
<td>Fraction of planet hosts ($f_p$)</td>
<td>0.33</td>
</tr>
</tbody>
</table>
EVOlution of $r_c/r_h$ AND $\rho_c$

Core Radius

- A regular non-core-collapsed cluster
- Low central density

Central Density
Evolutionary stages of dense star clusters
Evolutionary stages of dense star clusters

expansion from SE mass loss
Evolutionary stages of dense star clusters

Expansion from SE mass loss

$10-100$ Myr

$t$
Evolutionary stages of dense star clusters

expansion from SE mass loss

slow contraction

\[ \frac{r_c}{r_h} \]

10-100 Myr

t
Evolutionary stages of dense star clusters

expansion from SE mass loss

slow contraction

$\frac{r_c}{r_h}$

10-100 Myr

few 10 Gyr

$\text{t}$

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Evolutionary stages of dense star clusters

- Expansion from SE mass loss
- Slow contraction
- Binary-burning

$r_d/r_h$

10-100 Myr

few 10 Gyr

$t$
Evolutionary stages of dense star clusters

10-100 Myr

slow contraction

binary-burning

few 10 Gyr

many Hubble times
Evolutionary stages of dense star clusters

- Expansion from SE mass loss
- Slow contraction
- Binary-burning
- GT oscillations

- 10-100 Myr
- Few 10 Gyr
- Many Hubble times

$t$
Evolutionary stages of dense star clusters

- Expansion from SE mass loss
- Slow contraction
- Binary-burning
- GT oscillations
- Many Hubble times
- Until dissolution

$t$

$r_c/r_h$

10-100 Myr

few 10 Gyr

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$n(< R_{\text{planet}})$

$R_{\text{planet}} (R_\oplus)$

$K_p < 18$

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PLANETS ESCAPED FROM CLUSTER

$N_{\text{esc}}(t)/N(0)$

- Planetary objects
- Ionized planets
- Bound planets

$t$ (Myr)