Dynamics of Binary Stars and their Planets

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Multiplicity in Star Formation
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Planets are Common

- Nearly 10% of FGK stars have at least one Jovian planet within 10 AU (>200 detected).

- Tip of the iceberg? Saturn? Neptune? Earth?

- We will know much more in the next decade.
Binaries have Planets too

- 20-30% of stars with planets have a stellar companion (e.g., Raghavan et al. 2006).
- Most orbits have separations > 100 AU.
- However, wide systems selected:

\[ D = 10-50 \text{ pc} \]

separation < 10–50 AU \( \Rightarrow \) \( \theta \lesssim 1'' \)

\( \Rightarrow \) Unresolved
### HD 188753

#### Inner Pair
- $M_{B1} = 1 \, M_{\text{Sun}}$
- $M_{B2} = 0.7 \, M_{\text{Sun}}$
- $\alpha_B = 0.7 \, \text{AU}$

#### Outer Pair
- $M_A = 1.1 \, M_{\text{Sun}}$
- $e_{AB} = 0.5$
- $\alpha_{AB} = 12.3 \, \text{AU}$

#### Planet
- $M_p \sim M_{\text{Jup}}$
- $P_{\text{orb}} = 3.35 \, \text{d}$

(Konacki 2005)

**But...**
Alas...

- Eggenberger et al. (2007) find no evidence for a planet in HD 188753.

- But same ideas apply.
Influence of the Companion

**Truncation Radius**

\[ R_t \sim 0.3 \ a (1-e)^{1.2} \]

(Pichardo et al. 2005)

\[ R_t \sim 1 \ \text{AU} \]

in HD 188753
Binaries are Hostile to Planets

Tidal truncation inside ‘snow line’ at 1-3 AU.
(Hayashi 1981; Sasselov & Lecar 2000)

Insufficient mass/time within $R_t$.
(Jang-Condell 2007)

Stirring/Heating of the disk.
(Thébault et al. 2004, 2006)
Binaries are Hostile to Planets

- Spiral waves dissipate as thermal energy.
- Gas temperature, particle velocities increase.
- Collapse and core-accretion less likely.

Even binaries with $a \sim 50$ AU ($R_t \sim 10$ AU) are potentially hostile to giant planet formation.
Binaries with $a/D < 2''$ tend to be cut.

$D \sim 20-50$ pc $\Rightarrow$ cut on $a < 40-100$ AU.

We expect that $R_t > 5-10$ AU a requirement.

$a/R_t \sim 3-4 \Rightarrow$ problems for $a < 20-40$ AU.

‘Close’ Binary $\Rightarrow$ Binary $a < 50$ AU.
‘Close’ Binaries with Planets

(Pfahl & Muterspaugh 2006)

<table>
<thead>
<tr>
<th>Object</th>
<th>$a$ (AU)</th>
<th>$e$</th>
<th>$M_1/M_2$</th>
<th>$R_t$ (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 188753</td>
<td>12.3</td>
<td>0.50</td>
<td>1.06/1.63</td>
<td>1.3</td>
</tr>
<tr>
<td>$\gamma$ Cephei</td>
<td>18.5</td>
<td>0.36</td>
<td>1.59/0.34</td>
<td>3.6</td>
</tr>
<tr>
<td>GJ 86</td>
<td>$\sim$20</td>
<td>$\ldots$</td>
<td>0.7/1.0</td>
<td>$\sim$5</td>
</tr>
<tr>
<td>HD 41004</td>
<td>$\sim$20</td>
<td>$\ldots$</td>
<td>0.7/0.4</td>
<td>$\sim$6</td>
</tr>
<tr>
<td>HD 196885</td>
<td>$\sim$25</td>
<td>$\ldots$</td>
<td>1.3/0.6</td>
<td>$\sim$7</td>
</tr>
</tbody>
</table>

* Secondary a binary! (Konacki 2005; but see Eggenberger et al.)
† Secondary a white dwarf. (Mugrauer & Neuhauser)
‡ Secondary orbited by a brown dwarf in the desert. (Zucker et al. 2004)

4 of $\sim$3000 stars surveyed 
+ Selection Effects $\Rightarrow F_{cbp} \sim 1\%$

(Bonavita & Desidera 2007)
A Dynamical Backdoor

Maybe $AB$ was much wider initially.

Perhaps $A$ initially had a different companion in a wide orbit.

What if $A$ was born single?

All require birth in a cluster!
Dynamical Pathways

The Players
A: Planet Host
B: Binary Companion
C: Catalyst Star

The Plays
I: $AB+C \rightarrow AB+C$
II: $AC+B \rightarrow AB+C$
III: $A+BC \rightarrow AB+C$

(AB shrinks)
Dynamical Pathways

The Players

A: Planet Host
B: Binary Companion
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The Plays

I: AB+C → AB+C
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Dynamical Pathways

The Players
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The Plays
I: AB+C → AB+C
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III: A+BC → AB+C

(A replaces C)
Stellar Birth Clusters

~90% of all stars form in clusters with $10^2$-$10^3$ members.
(e.g., Lada & Lada 2003)

Most clusters dissolve in <100 Myr.
(e.g., Wielen 1985)

Within 100 pc, there are $\sim 10^5$ binaries from thousands of clusters.
Star Cluster Basics

Cluster of Stars
(and Gas and Dust)

Mean Properties

- Number of stars
  - $N$

- Radius containing half of the mass
  - $r_h$

- Velocity Dispersion
  - $\sigma = \left(\frac{G M_c}{r_h}\right)^{1/2}$

- Mean density within $r_h$
  - $n_h = \frac{3N}{8\pi r_h^3}$

$M_c \sim 3N \langle m \rangle$
Star Cluster Basics

Cluster of Stars
(and Gas and Dust)

Embedded Phase

\[ r_h \sim (N/100)^{1/2} \text{ pc} \]

\[ n_h \sim 10(N/100)^{-1/2} \text{ pc}^{-3} \]

\[ \sigma \sim (N/100)^{1/4} \text{ km s}^{-1} \]

Lifetimes < 5-10 Myr.
Set by gas/dust expulsion.
Only ~10% of clusters survive.

M_c \sim 3N\langle m \rangle
Star Cluster Basics

Cluster of Stars (and Gas and Dust)

Open Clusters

- $r_h \sim 1 \text{ pc}$
- $n_h \sim 10(N/100) \text{ pc}^{-3}$
- $\sigma \sim (N/100)^{1/2} \text{ km s}^{-1}$

Lifetimes set by dynamics.

- $t_{rel} \sim (r_h^3/GM_c)^{1/2} (0.1N/\ln N)$
- $\sim \text{ few } (N/100)^{1/2} \text{ Myr}$

N drops with

- $T_{1/2} \sim 100 (N/100)^{1/2} \text{ Myr}$
Star Cluster Basics

Cluster of Stars
(and Gas and Dust)

All Clusters

\[ p(N) \propto N^{-2} \]
\[ p(a) \propto a^{-1} \]
\[ f_b \sim f_s \sim 0.5 \]
\[ f_{cb} \sim 0.5 \]

\[ M_c \sim 3N\langle m \rangle \]
Scattering Dynamics

Cross Section: $\Sigma \sim \pi [\alpha^2 + 2\alpha G M_{123}/u^2]$ \quad (u\sim\sigma)$

For close binaries: $GM_{12}/[\alpha \sigma^2] >> 1$

$\Rightarrow \Sigma \sim 2\pi \alpha G M_{123}/\sigma^2$

(Approximate exchange cross section.)
Scattering Statistics

Rate per binary: \( f_p \ n_s \ \langle \Sigma \sigma \rangle \)
(average over singles)

Number per cluster: \( \int dt \ \int dV \ n_b \ f_p \ n_s \ \langle \langle \Sigma \sigma \rangle \rangle \)
(average over singles and close binaries)

\(~0.003 \ (N/100)^2\)

Sum over clusters:
\( F_{cbp}(\text{theory}) \sim 0.001 \)
Result

\[ F_{\text{cbp}}(\text{theory}) \sim 0.1 \ F_{\text{cbp}}(\text{obs}) \]

Maybe nature knows how to make giant planets in close binaries.

???
What’s Next?

• More observations.
  (Konacki; Eggenberger et al.; Lane, Muterspaugh, et al.)

• Census of stellar birth clusters.
  (Taurus or Orion?)

• Better calibration of dynamics.
  (few-body; full N-body models)