Planetary Systems in Stellar Clusters

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Our Own Solar System
How to detect planets around other stars

Doppler Shift due to Stellar Wobble

Unseen planet
Detecting planets with transits
Number of planets found

Number of extrasolar planet discoveries per year as of 27 August 2010, with colors indicating method of detection:

- **radial velocity**
- **transit**
- **timing**
- **astrometry**
- **direct imaging**
- **microlensing**

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A QUESTION:

How do the observed extrasolar planet systems compare to our own solar system?
Planetary orbits

![Planetary orbit diagram](image-url)
Known multiple-planet systems

(Lovis et al 2010)
QUESTIONS:

Why are jupiter-mass planets so close to their stars?

Why are planets on eccentric orbits?
Stable Systems

Something Happens

Unstable Systems
What is the something?

The something is either i) close encounters within young stellar clusters or ii) exchange encounters which leave planetary systems in binaries.

Strong planet-planet interactions within planetary systems may follow.
Orion nebula and Trapezium cluster (2MASS image)

All stars are formed in some sort of cluster.
Open cluster properties

(Lamers et al 2005, Kharchenko et al 2005)
Stellar encounter timescales

Cross section is given by

\[
\sigma = \pi R_{\text{min}}^2 \left( 1 + \frac{2G(M_1 + M_2)}{R_{\text{min}}V_\infty^2} \right)
\]

Timescale for a given star to undergo an encounter is

\[
\tau_{\text{enc}} \simeq 3.3 \times 10^7 \text{yr} \left( \frac{100 \text{ pc}^{-3}}{n} \right) \left( \frac{V_\infty}{1 \text{ km/s}} \right) \left( \frac{10^3 \text{ AU}}{R_{\text{min}}} \right) \left( \frac{M_\odot}{M_\odot} \right)
\]
Simulate open cluster evolution

Evolve open clusters considering a range of sizes and masses.

Place some stars in binaries whilst others are initially single.

Trace stellar histories: log all the close encounters between two stars and binary/single encounters.

(Malmberg et al 2007b)
Singleton:

1) a star which has not formed in a binary,

2) a star which has not later spent time within a binary system,

3) a star which has not suffered close encounters with other stars.
How common are singletons?

N=700 stars, R=2-4 pc

(Malmberg et al 2007b)
The long term effect of fly-bys (within 100 AU)

The fraction of solar-mass stars with four gas giants in a cluster of 700 stars that lose at least one planet within 100 million years of a close fly-by: \(0.15\)

The four gas giants $10^8$ years after fly-by ($r_{\text{Min}} < 100$ AU)

Fraction of solar-mass stars with initially four gas giants in a cluster of 700 stars having a planet with $a > 100$ au 100 million years after fly-by: 0.02

A planet ~330 AU from host star

Fig. 1.— Young star 1RXS J160929.1-210524 and its faint, planetary mass candidate companion. Blue, green, and red represent images taken in J, H, and Ks, with intensities scaled such that they are proportional to the photon rates inferred from the 2MASS magnitudes of the primary.

(Lafrenière et al 2008)
Post fly-by systems consisting of a single planet bound to the intruder star immediately after the fly-by

Effects of being in a binary

If the planetary system and stellar binary are highly inclined, the Kozai Mechanism will make the planetary orbits highly eccentric.

Strong planet-planet scattering will then occur for multiple-planet systems.

For high inclinations planets’ orbits may become extremely eccentric leading to tidal circularisation.
The Kozai Mechanism

For low inclinations, see small oscillations in eccentricity only.

If $i_0 > i_c$ where $\sin(i_c) = \sqrt{2/5}$

see oscillations in inclination between $i_0$ and $i_c$

$$\sqrt{a(1 - e^2)\cos(i)}$$ is constant

$$e_{max} = \sqrt{1 - 5/3\cos^2(i_0)}$$
Evolution of a planet within a stellar binary

\hspace{1cm}
i=60\ degrees
The four gas giants in a binary

(Malmberg, Davies & Chambers, 2007; Malmberg & Davies 2009)
Evolution of our solar system in a binary

(Malmberg, Davies & Chambers, 2007; Malmberg & Davies 2009)
Could the Kozai Mechanism produce hot jupiters?

The idea is that Kozai produces extremely eccentric systems, which could undergo tidal interactions with the star, leaving the planet on a much tighter orbit.

Fabrycky & Tremaine (2007)

Wu, Murray & Ramsahi (2007)

Probably need to consider primordial binaries as well as initially-single stars to get reasonable rates
Hot Jupiters can sometimes be highly inclined

(eg Hébrard et al 2008, Triaud et al 2010)
A planetary flow diagram

- Solar System
  - exchange into binary
  - fly-by
  - singleton

- PSS
  - Kozai Mechanism

- P–P interaction
  - Tidal interaction

- SSIB

- Solar System
- Exoplanet systems
- Hot jupiters
The bottom line

Considering single, solar-mass stars with four gas giants in a cluster of 700 stars:

Fraction of stars losing at least one planet due to stellar binary companions \( \sim 0.05 \)

Fraction of stars losing at least one planet in 100 million years due to fly-bys \( \sim 0.15 \)

Numbers change only slowly with \( N \) (see MDH2010).

In other words: fly-bys and binary companions can make stable planetary systems unstable interestingly often.
Conclusions

Encounters within stellar clusters may damage/destroy planetary systems.

Planetary systems left within binaries may be damaged via eccentricities induced by the Kozai Mechanism.

Singletons are stars which are formed single and are never within binaries or have close encounters.

Are some extrasolar planets messed-up solar systems?