Planetary Systems in Stellar Clusters

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A QUESTION:

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

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

Why are planets on eccentric orbits?
One IDEA:

Planets migrate within disk around star.
Planet migration inside a disk

(eg. Armitage 2007)
An extrasolar planetary system with three Neptune-mass planets

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Over the past two years, the search for low-mass extrasolar planets has led to the detection of seven so-called ‘hot Neptunes’ or ‘super-Earths’ around Sun-like stars. These planets have masses 5-20 times larger than the Earth and are mainly found on close-in orbits with periods of 2-15 days. Here we report a system of three Neptune-mass planets with periods of 8.67, 31.6 and 197 days, orbiting the nearby star HD 69830. This star was already known to show an infrared excess possibly caused by an asteroid belt within 1\text{AU} (the Sun–Earth distance). Simulations show that the system is in a dynamically stable configuration. Theoretical calculations favour a mainly rocky composition for both inner planets, while the outer planet probably has a significant gaseous envelope surrounding its rocky/icy core; the outer planet orbits within the habitable zone of this star.

(Lovis et al 2006)

(Alibert et al 2006)
Known multiple-planet systems

(Lovis et al 2010)
A problem with migration inside a disk

Why are so many of the observed planets on eccentric orbits?
A Different Idea
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

\[ \tau_{\text{enc}} \approx 3.3 \times 10^7 \text{yr} \left( \frac{100 \text{ pc}^{-3}}{n} \right) \left( \frac{V_{\infty}}{1 \text{ km/s}} \right) \left( \frac{10^3 \text{ AU}}{R_{\text{min}}} \right) \left( \frac{M_\odot}{M_t} \right) \]
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)
Effects of close encounters

Extremely close fly-by encounters may result in the direct ejection of planets.

Other planets may remain bound but on tighter and more eccentric orbits.

Even very small perturbations can sometimes lead to significant outcomes via planet-planet interactions within planetary systems.
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

(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.
Important point

Stars with planetary systems which exchange into binaries may later be single again.

For example binary may be broken up in an encounter with another (harder) binary.
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 \( i_c \)

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

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

\[ i=60 \text{ degrees} \]
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)
Hot Jupiters can sometimes be highly inclined

(eg Hébrard et al 2008, Triaud et al 2010)
How common is Kozai-induced tidal capture?

Want to produce hot jupiters in \( \sim 0.005 \) solar-like stars

Fraction of random binary orientations which lead to tidal capture for planet at 5 AU \( \sim 0.05 \)

But some stars in many binaries/orientations
Potential fraction of stars with hot jupiters

(Davies et al, in prep)
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*Probably need to consider primordial binaries as well as initially-single stars to get reasonable rates*
A planetary flow diagram

- Solar System
- Exoplanet systems
- Hot jupiters
- P–P interaction
- Tidal interaction
- Kozai Mechanism
- SSIB
- PSS
- fly-by
- exchange into binary
- singleton
- time
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?