Planetary Systems in Stellar Clusters

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Planetary orbits

![Diagram showing the relationship between semi-major axis (AU) and eccentricity.](image-url)
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 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

(Hovis et al. 2010)
What about eccentricities?
A CLAIM:

Think of a planetary system containing a number of gas giants. Either:

1) Planetary system is self-unstable, leading to the ejection of giant planets, leaving others on eccentric orbits, or

2) Planetary system is not self-unstable (rather like our own solar system).
Known multiple-planet systems

HD 40307
GJ 581
HD 69830
HD 115617
HD 10180
HD 181433
Solar System
HD 37124
GJ 876
55 Cnc
HD 160691
HIP 14810
Ups And
HD 74156
HD 125612

Semi-major axis [AU]

(Lovis et al 2010)
Stable Systems

Something Happens

Unstable Systems
What is the something?

The something is either i) close encounters within young stellar groupings 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 grouping.
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 cluster evolution

Evolve 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

Entire cluster lifetime

S

0.8-1.2 msol

B

F

0.000

0.004

0.067

0.000

0.000

0.780

0.149

(Malmberg et al 2007b)
The First Ten Million Years
Distribution of encounters over time

\[ f(t) \text{ (} r_{\text{min}} < 1000 \text{ au}) \]

- $N = 150$
- $N = 300$
- $N = 500$
- $N = 700$
- $N = 1000$
How common are singletons in first 10 Myr?

0.8-1.2 msol
0.324

1.3-1.7 msol
0.701

1.8-2.5 msol
0.673

(Malmberg et al 2007b)
Simulating star-disc encounters

(Theis, Kroupa & Theis 2005)

(Forgan & Rice 2009)
Effect of star-disc encounters

Disc trimmed to about one third of close encounter distance, eg $r_{\text{min}}$ of 200 AU restricts disc radius to about 60 AU.

\[ r_{\text{min}} \sim 200 \left( \frac{R_{\text{cluster}}}{2\text{pc}} \right) \left( \frac{N}{2000} \right)^{-1} \text{AU} \]

(Adams & Laughlin 2001)
Disc evaporation

UV radiation from a cluster of stars can lead to disc evaporation.

For a cluster of about 1000 stars, the disc radius can be reduced in 10 Myr to a radius given by

\[ r_{\text{disc}} \simeq 36\text{AU}(M_*/M_{\odot}) \]

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 \(\sim 330\) 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 \(K_s\), 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.
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)
How common is Kozai-induced tidal capture?

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

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

But some stars in many binaries/orientations

*Probably need to consider primordial binaries as well as initially-single stars to get reasonable rates*
A planetary flow diagram

Solar System

SSIB

PSS

Singleton

SSIB

Kozai Mechanism

P–P interaction

Tidal interaction

time

Solar System

Exoplanet systems

Hot jupiters

fly–by

exchange into binary
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 groupings 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?