Orbital Dynamics of Planetary Systems

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How do planetary systems evolve?

Planetary systems evolve due to the exchange of angular momentum and/or energy:

1) among multiple planets
2) between planets and planetesimal disks
3) between planets and other stars
4) via tides with stellar host
Two-body problem (Brahe, Kepler, Newton)

Planets orbit in ellipses around the host star.

\[ E = -\frac{GM_1 M_2}{2a} \]

\[ e^2 = 1 + \frac{2EJ^2}{G^2 \mu^3 M^2} \]
What happens to planetary systems?

For well-separated two-planet systems, get periodic oscillations in eccentricity and inclination.

Can get collisions or ejections if planets get close enough - planets do the work on each other.

Thus qualitative changes in the architecture of planetary system can occur.

Can get changes due to encounters in clusters or stellar companions or planet-disk interactions.
The Plan

1) Begin with our Solar System.

2) Then tightly-packed systems.

3) Interactions between planetary systems and other stars (*crowded places*).

4) Hot jupiters.
Our Solar System
Our Solar System

$t = 0.0 \text{ yr}$
The giant-planet sub-system of the Solar System is stable although the terrestrial-planet sub-system is marginally unstable with a small chance of planet-planet encounters during the lifetime of the Sun.

e.g. Sussman & Wisdom 1992; Laskar 1994, 2008; Murray & Dermott 1999; Guzzo 2005; Hayes 2008; Batygin & Laughlin 2008; Laskar & Gastineau 2009
Eccentricity of Jupiter and Saturn

Eccentricity of Earth
Interactions with planetesimal disks will cause planets to migrate which in turn can lead to instabilities within a planetary system. This process probably played an important role in the early history of our own Solar System.

e.g. Fernandez & Ip 1984; Hahn & Malhotra 1999; Gomes et al 2004; Tsiganis et al 2005; Gomes et al 2005; Levison et al 2011
Planet-disk interactions in our Solar System

(Data from Levison et al, 2011, AJ, 142, 152)
Aging systems may become unstable when the host star evolves to become a white dwarf, and loses mass, as the relative strength of the planet-planet interactions increase compared to the interactions between the planets and host star.

e.g. Duncan & Lissauer 1998; Debes & Sigurdsson 2002; Veras et al 2013; Voyatzis et al 2013
Kepler systems are also flat

By considering the ratio of three, two and single-planet transits, one gets a limit on mutual inclinations.

Kepler Catalogue of Candidate Systems

Very large catalogue of multiple planet systems found by Kepler through transits.

From first 16 months of data:

84 triples, 245 doubles, and 1425 single transits
Making everything from 3p systems

(Johansen, Davies, Church & Holmelin 2012)
Tightly-packed systems
Secular interactions cause the redistribution of angular momentum amongst planets in a system. In systems with a sufficiently large angular momentum deficit (AMD), such redistribution can lead to close planetary encounters.

\[ \text{AMD} \equiv \sum_k \Lambda_k \left( 1 - \cos i_k \sqrt{1 - e_k^2} \right) \]

\[ \Lambda_k = \frac{M_k M_*}{M_k + M_*} \frac{1}{\sqrt{G(M_* + M_k) a_k}} \]
Secular chaos could produce hot Jupiters

Planet-planet scattering in tighter planetary systems can lead to close encounters between planets. The timescale before a system undergoes such encounters is a strong function of the separation of planets.

e.g. Chambers et al 1996; Marzari & Weidenschilling 2002
An unstable system containing three Jupiters

(Ross Church, private comm.)

see also: Quillen (2011)
Instability time as a function of separation

\[ R_{\text{hill,m}} \equiv \left( \frac{M_k + M_{k+1}}{3M_*} \right)^{1/3} \times \frac{a_k + a_{k+1}}{2} \]

The outcome of planetary close encounters is a function of the Safronov number.

\[ \Theta^2 = \left( \frac{M_p}{M_*} \right) \left( \frac{R_p}{a_p} \right)^{-1} \]

Collisions dominate when the planetary surface escape speeds are smaller than orbital speeds.

Planetary scattering will be more common when the surface escape speeds are larger than the planetary orbital speeds in a system.
Do planets scatter or collide?

Strong planet-planet interactions tend to lead to scatterings if $V_{\text{esc},p} > V_{\text{orb},p}$

Strong planet-planet interactions tend to lead to collisions if $V_{\text{esc},p} < V_{\text{orb},p}$

$11 < 30 < 64$

Collisions can shape planetary systems: eg Kepler 36

ROCK vs ICE vs GAS
The observed eccentricity distribution can be explained as an outcome of planet-planet scattering in unstable systems. Massive planets have to be formed in systems with other massive planets in order to reproduce the observed correlation between planetary mass and orbital eccentricity.

e.g. Adams & Laughlin 2003; Moorhead & Adams 2005; Juric & Tremaine 2008; Chatterjee et al 2008; Ford & Rasio 2008; Raymond et al 2010; Beaugé & Nesvorný 2012
Planets are predicted to pass through a phase of wide orbits within unstable planetary systems as ejections occur only after several scatterings. Imaging surveys will therefore inform us about the frequency of unstable systems.

Scharf & Menou 2009;
Veras, Crepp & Ford 2009;
Malmberg, Davies & Heggie 2011
The four gas giants $10^8$ years after fly-by ($r_{\text{min}} < 100$ AU)

Crowded Places

The birth environments of planetary systems
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,

   (eg. Rasio & Ford 1996; Juric & Tremaine 2008)

   OR

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

   (eg. Lovis et al 2010; Kepler Candidates)
KEY IDEA:

*Close encounters* with other stars,

or

*Exchange encounters* which leave planetary systems in binaries

can destabilise planetary systems, leaving planets on more bound and eccentric orbits.

*Such encounters can occur in dense birth environments.*
Fly-by encounters in stellar clusters will occur in dense birth environments. Such encounters may lead to the direct ejection of planets in some cases. In other encounters, perturbations to the planetary orbits lead to instabilities on longer timescales. The intruding star may also pick-up a planet from the system.

\[
\tau_{\text{enc}} \simeq 3.3 \times 10^7 \text{yr} \left( \frac{100 \text{ pc}^{-3}}{n} \right) \left( \frac{v_\infty}{1 \text{ km/s}} \right) \left( \frac{10^3 \text{ AU}}{r_{\text{min}}} \right) \left( \frac{M_\odot}{M} \right)
\]

e.g. Adams et al 2006; Malmberg et al 2007; Proszkow & Adams 2009; Allison et al 2009; Parker & Quanz 2012.
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

Exchange into binaries can occur in stellar clusters. Planetary systems may be de-stabilised by the perturbing effect of the companion star through the Lidov-Kozai mechanism where the outer planet suffers periods of higher eccentricity leading it to have strong encounters with other planets.

e.g. Lidov 1962; Kozai 1962; Innanen et al 1997; Malmberg et al 2007; Malmberg & Davies 2009
Evolution of our solar system in a binary

The four gas giants in a binary

Fraction of solar-like stars suffering encounters for cluster containing 700 stars

<table>
<thead>
<tr>
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<th>Close fly-by</th>
<th>Binary earlier</th>
<th>Binary today</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS-10</td>
<td>~0.10</td>
<td>~0.05</td>
<td>~0.03</td>
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<tr>
<td>CL-10</td>
<td>~0.15</td>
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<tr>
<td>WSN-all</td>
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<tr>
<td>CL-all</td>
<td>~0.20</td>
<td>~0.50</td>
<td>~0.10</td>
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(Church, Davies & Bonnerot, in prep.)

*In other words: fly-bys and binary companions can make stable planetary systems unstable interestingly often.*
Hot Jupiters
The formation of hot jupiters is an interesting question. Observations using the Rossiter-McLaughlin effect show that a number of hot jupiters are highly-inclined compared to what would be expected given the stellar rotation.

e.g. Triaud et al 2010
The origin of hot Jupiters through dynamical interactions may involve one of five possible routes:

1) Lidov-Kozai evolution of a one-planet system perturbed by a binary stellar companion;
2) Lidov-Kozai evolution in a multiple-planet system;
3) scattering of multiple planets;
4) secular evolution unrelated to the Kozai resonance;
5) the re-orientation of circumstellar disks before planets form via interaction

e.g. Innanen et al 1997; Wu & Murray 2003; Takeda & Rasio 2005; Fabrycky & Tremaine 2007; Malmberg & Davies 2009; Bate et al 2010; Naoz et al 2011; Nagasawa & Ida 2011; Beaugé & Nesvorný 2012; Batygin 2012; Dawson et al 2012
Summary

1) Secular interactions and AMD.

2) Instability timescales vary enormously.

3) Multiplicity matters.

4) Scattering can match observed eccentricities.

5) Flybys and binary companions can mess up a planetary system.

6) Hot jupiters may form through one of several dynamical processes.