Multi-body systems

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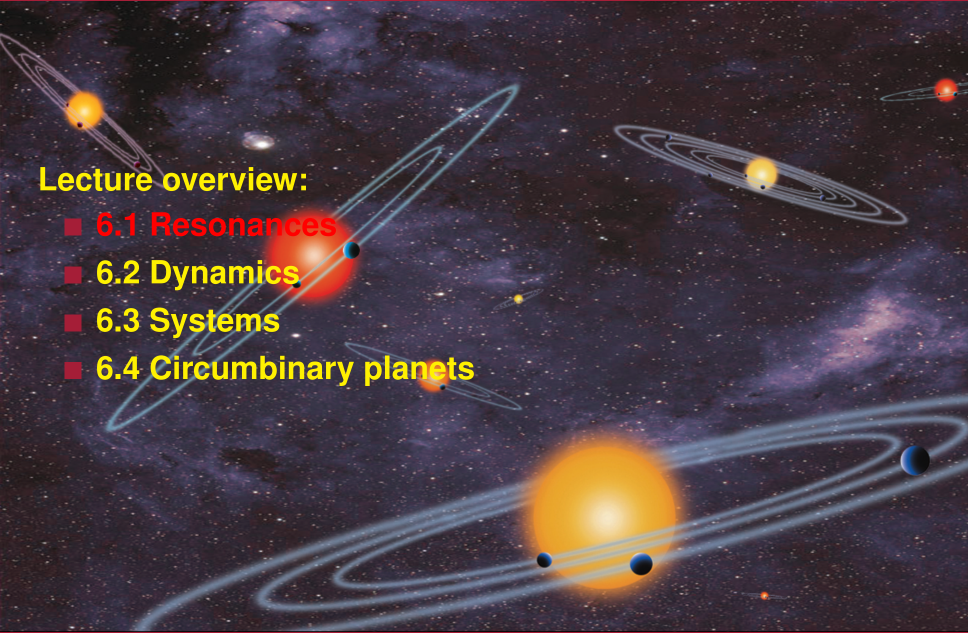
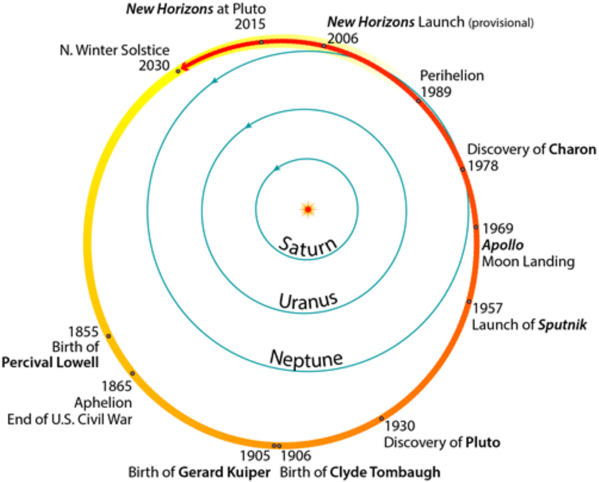


Lecture overview:

- 6.1 Resonances
- 6.2 Dynamics
- 6.3 Systems
- 6.4 Circumbinary planets

Example from the Solar System

Orbital Periods: Neptune: 165yrs, Pluto: 248yrs
Semi-major axis: Neptune: 29.7 AU, Pluto: 35.5 AU



(NASA: New Horizon Mission)

Eccentricity $e_p = 0.25$
crossing orbits

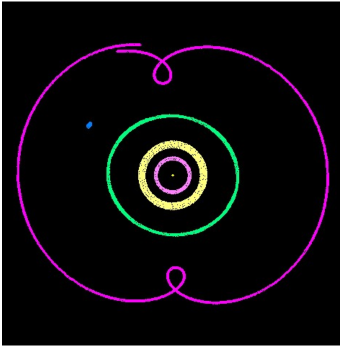
Stabilisation by:
3:2 Resonance
Neptune: 3 Orbits
Pluto: 2 Orbits

Pluto shares orbits with plutinos

$\Rightarrow$ Pluto degraded from planet to dwarf planet

Pluto-Flyby on 14. July, 2015.

Example of orbits



(Gravity Simulator, Tony Dunn)

Planetary orbits:
in the corotating-frame of Neptune

Pluto
Neptuns
Uranus
Saturn

Orbits avoid close encounters

Pluto maximizes its separation from Neptune

The resonant condition stabilizes Pluto's orbit

Definition - Mean motion resonance

A Mean Motion Resonance (MMR) is given by an integer ratio of their mean motions n_i

$$n_1/n_2 = p/q \qquad \text{mit} \qquad q, p \in N \tag{1}$$

n_i mean orbital velocity of i-th planet (1: inner, 2: outer planet)

The resonant angles are then defined (with $p > q$)

$$\Phi_k = p\lambda_2 - q\lambda_1 - p\varpi_2 + q\varpi_1 + k(\varpi_2 - \varpi_1), \tag{2}$$

where λ_i and ϖ_i are the mean longitudes and longitudes of periapse. The integer k in Eq. (2) satisfies $q \le k \le p$ and has $p - q + 1$ possible values. Of the $p - q + 1$ resonant angles, at most two are linearly independent, and at least 1 angle will librate (resonant condition)

Example 2:1 System ($p = 2$ and $q = 1$)

$$\Phi_1 = 2\lambda_2 - \lambda_1 - \varpi_1, \quad \Phi_2 = 2\lambda_2 - \lambda_1 - \varpi_2 \qquad (\Delta\varpi = \Phi_1 - \Phi_2) \tag{3}$$

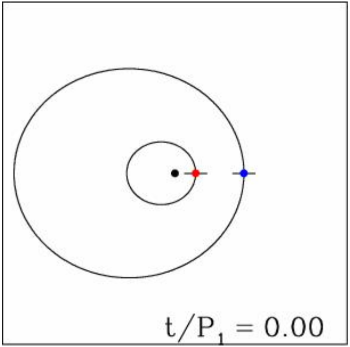
For details, see Book: Murray&Dermott *Solar System Dynamics*

Further notes on MMRs

- The resonant angles follow from an expansion of the perturbation potential between the two planets, that would move otherwise on unperturbed Kepler-orbits.
- Expand the perturbation in a Fourier-series
- The resonant angles are the stationary phases in the expansion
- If an angle Φ_i is in libration (i.e. covers a range smaller than $[0, 2\pi]$), then the system is said to be in a Resonance
- If both angles Φ_i (for a 2:1 resonance) librate (i.e. $\Delta\varpi$ as well) then the system is in apsidal corotation (ACR)

Animation of the observed motion of two systems

GJ 876: P_1=30d,P_2=60d



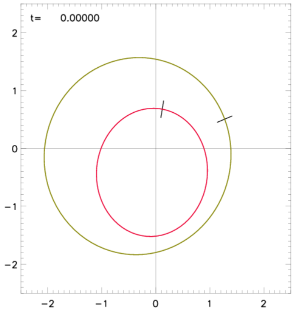
(Man Hoi Lee)

retrograde prcession

$\Delta\varpi$ in libration $(\Delta\varpi)_{max} \approx 30^\circ$

apsidal corotation

HD 128311: P_1=458d,P_2=928d

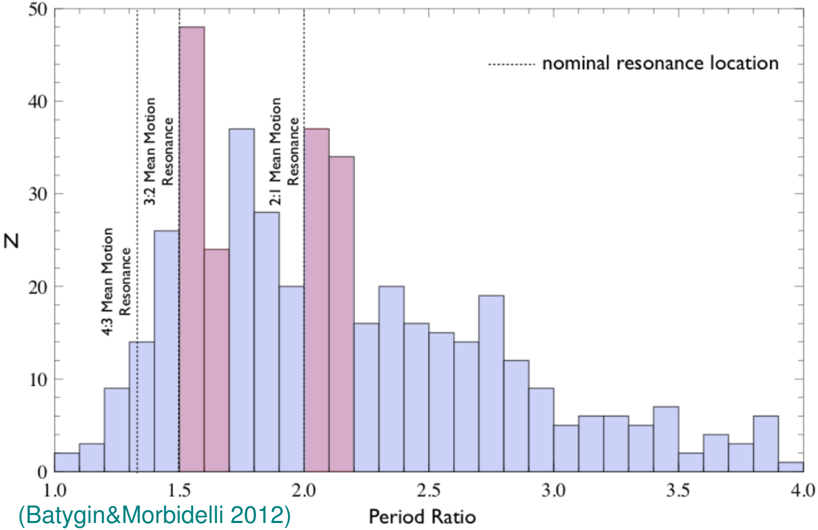


(Zsolt Sándor & Peter Klagyivik)

Planet 1: retrograde Precession

$\Delta\varpi$ circulates

Distance of periastrons: $\Delta\varpi = \varpi_2 - \varpi_1$

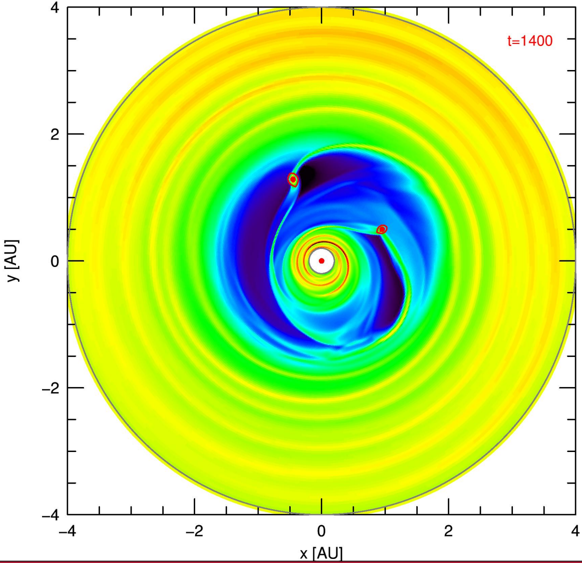


(Batygin&Morbidelli 2012)

- Higher numbers near 2:1 and 3:2 resonances
- but the systems lie slightly shifted from the resonance

Formation of a resonant system

2 massive planets in disk (in HD 73526 $\approx 2.5 M_{\mathrm{Jup}}$ each)



Two planets:
joint, large gap

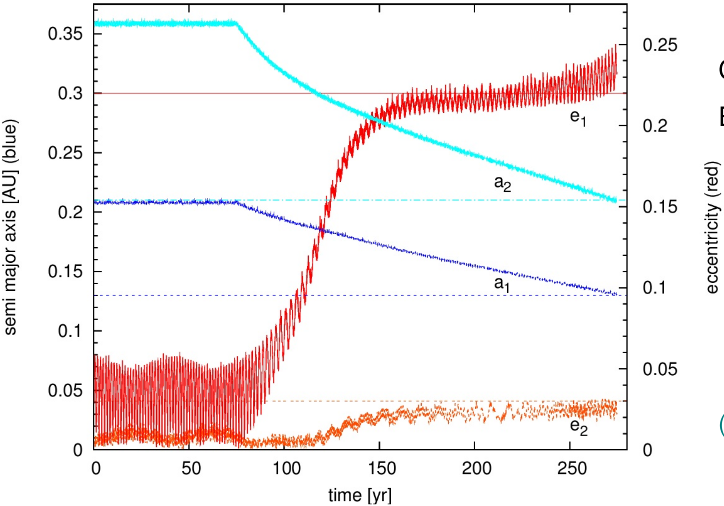
Outer planet :
Pushed inward
by outer disk

Inner planet :
Pushed outward
by inner disk

Separation reduction:
Resonant capture

(Sandor ea. 2007)

Here: System-parameter of GJ 876 (damping of inner & outer disk)



Compactification

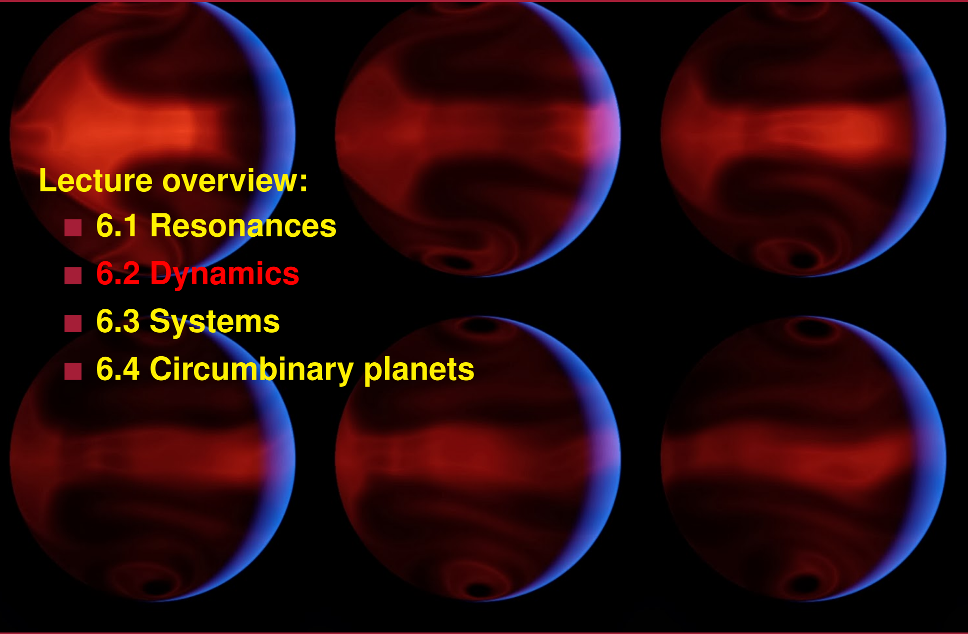
Excitation

(Crida ea 2008)

System ends in: apsidal corotation, with correct eccentricities

Less disk damping: $\Rightarrow$ much higher e $\Rightarrow$ possible Instability

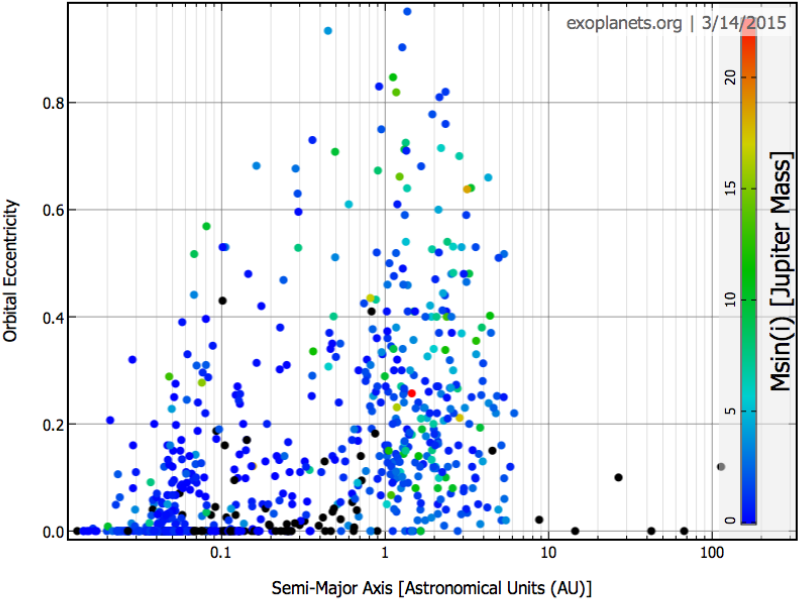
Organisation



Lecture overview:

- **6.1 Resonances**
- **6.2 Dynamics**
- **6.3 Systems**
- **6.4 Circumbinary planets**

Eccentricity vs. distance (RV-data)



Eccentricity and Inclination

What causes the high eccentricities and inclinations ?

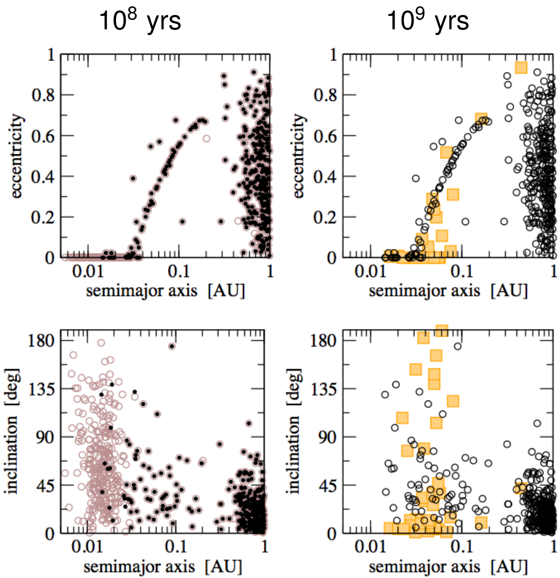
In principle 2 models:

- differential migration of planets in the disk:
  $\Rightarrow$ compact (resonant) configuration
  $\Rightarrow$ disk dissipates and reduces the stabilisation
  $\Rightarrow$ instability of planetary system
  $\Rightarrow$ excitation of e and i
  $\Rightarrow$ gravitational scattering processes

- by an additional, massive body (star, planet):
  (*tidally driven migration*, by the Kozai-effect)
  $\Rightarrow$ third body excites eccentricity (inclination) to high values
  $\Rightarrow$ oscillation of eccentricity and inclination (of planet)
  $\Rightarrow$ for very high $e \Rightarrow$ tidal interaction with central star
  $\Rightarrow$ damping of semi-major axis

(not by disk-planet interaction)

Migration and scattering processes



N-body simulations with 3 or 4 planets

Start with:
- system near resonance

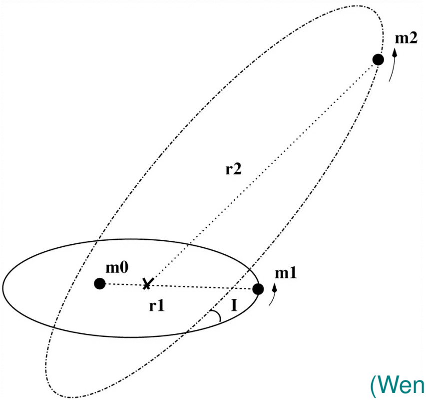
Consider:
- Star-Planet interaction

Black: Dots & circles
Planets after 10^9 yrs
In brown - Kreise:
Objekts after 10^8 yrs
In orange - squares:
Obsevations

For more details:
(Beauge & Nesvorny 2012)
(Juvic & Tremaine 2008)

Kozai-Mechanism

A main-belt asteroid in the Solar System moves under the influence of the Sun and Jupiter. If the initial inclination of the body is higher than $i_0 > i_{crit} = 38^\circ$ the orbits will become highly eccentric (Kozai, 1962). Sometimes also Lidov-Kozai mechanism.



(Wen, 2003)

Consider a hierarchical restricted 3-body system

For asteroid:
m_0 = sun
m_1 = asteroid
m_2 = Jupiter

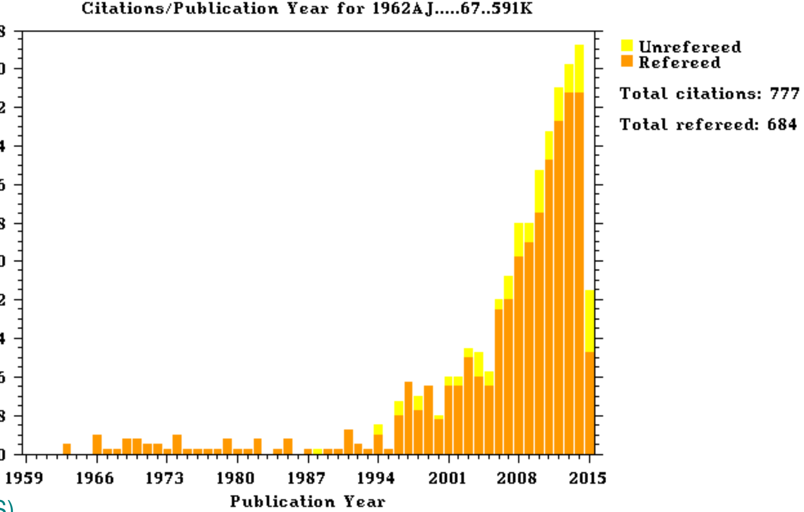
for proto planet:
m_0 = star
m_1 = planet
m_2 = secondary star

For the satellite, the orbit averaged equations of motion have a conserved quantity, $L_z = \cos(i)\sqrt{1-e^2}$, z is perpendicular to the orbit of the binary.

Kozai-Citations

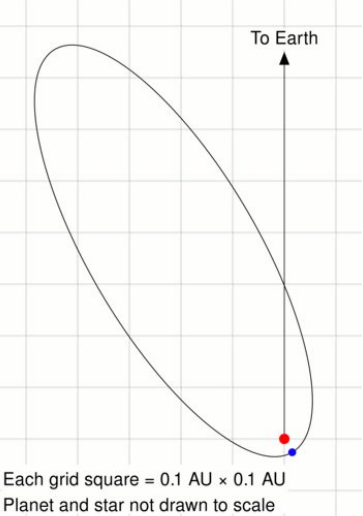
Secular perturbations of asteroids with high inclination and eccentricity

Kozai, Astronomical Journal, 1962



(ADS)

The planetary system HD 80606



(Wikepedia)

HD 80606
a highly eccentric planetary system

P_p = 111 d
m_p=3.94 M_{Jup}
a_p = 0.449 AU
e_p = 0.933

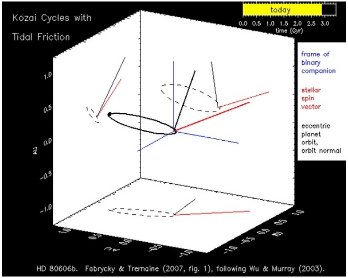
Kozai mechanism for HD 80606

Consider the motion of the planet in the HD 80606 system under the action of an additional secondary star at large distance

Todays parameter: m_p=3.94 M_{Jup}, a_p = 0.449 AU, e_p = 0.933

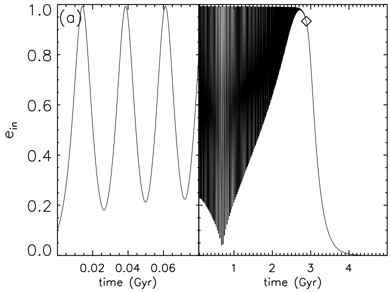
start with: a_p = 5 AU, i = 85.6°, e = 0.1
binary star parameter: m_{bin} = 1.1 $M_\odot$, a_{bin}=1000 AU, e_{bin} = 0.5

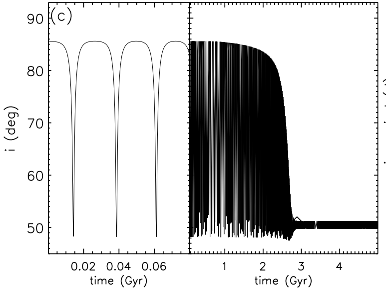
(e.g. Models by: Wu & Murray 2003, Fabrycky & Tremaine 2007)

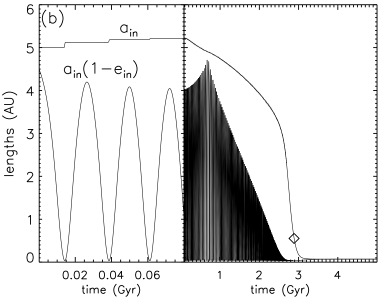


(Daniel Fabrycky, Harvard)

Orbital elements of HD 80606







Parameter:

	Start	Today
a_p (AU)	5	0.449
e	0.1	0.933
i	85.6°	50°

over a timescale of 3 Ga
the ◇ denotes the present position
(Fabrycky & Tremaine, 07)

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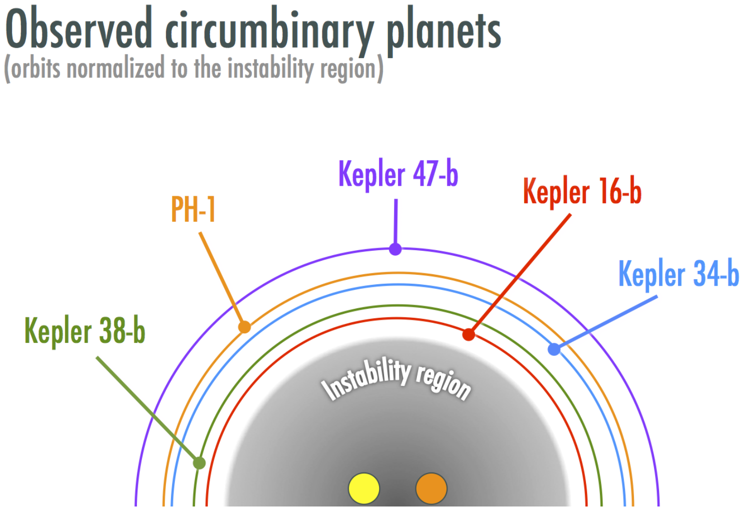


Presently 8 Kepler systems known. Orbits are unstable if a_p is smaller than 2-5 times a_{bin} (Holman & Wiegert, 1999)

Evolution of planets

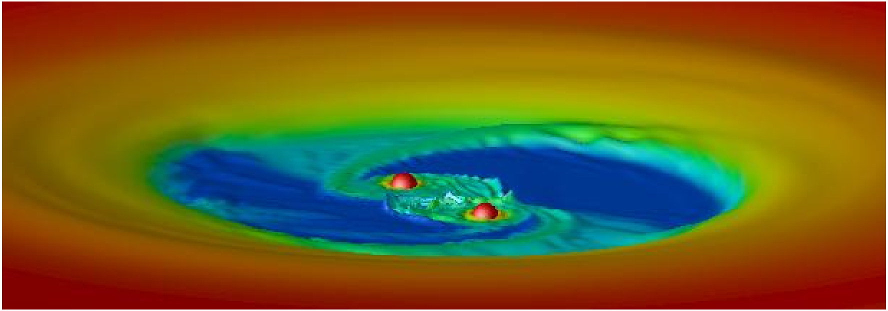
What brings the planets so close to the instability limit ?

Assume planets have formed further out in pp-disk (flat systems)
(not possible to form the in situ)

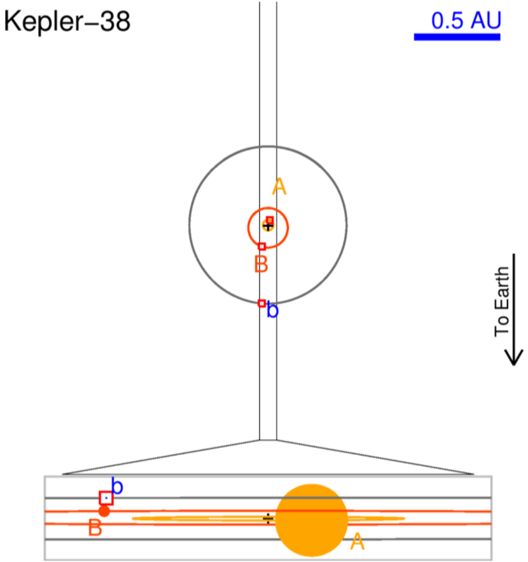
Study subsequent evolution of planets in disk (migration)

Analyse two cases: Kepler-38 and Kepler-34

(See work by Pierens & Nelson (2013))



Kepler 38: System Architecture



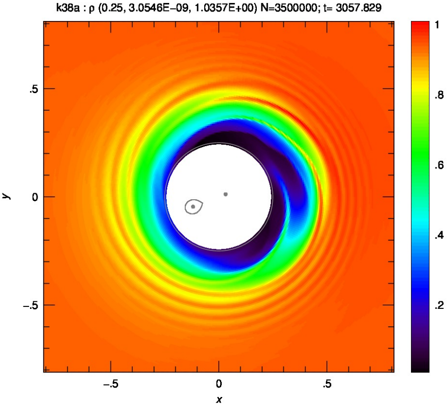
Binary Parameter:
(Kepler 38A,B)
$M_1 = 0.95 M_\odot$,
$M_2 = 0.25 M_\odot$
$P_B = 18.6$ days
$a_B = 0.15$ AU
$e_B = 0.10$

Planet Parameter:
(Kepler 38b)
$m_p = 0.36 M_{\rm Jup}$
$P_p = 105.6$ days
$a_p = 0.46$ AU
$e_p = 0.03$

Kepler 38 - Circumbinary Disk Model

Two-dimensional disk around central binary, hydrodynamics, α-viscosity no self-gravity. Isothermal and radiative disks

Animation of disk around Binary Star
(shown is surface density of inner disk)

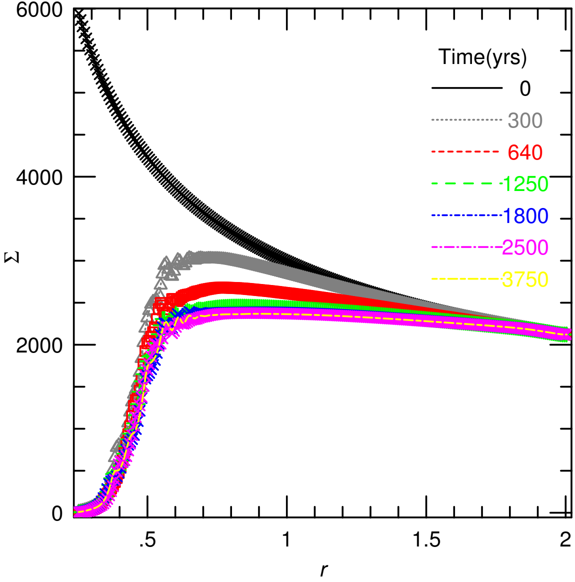


Disk Parameter:
Range: 0.25 - 2.0 AU
Mass: $3 \cdot 10^{-3}$ $M_\odot$
Sigma: 2000 g/cm^2
at 2 AU
Equation of state:
locally isothermal

With central binary:
truncates disk

(Kley & Haghighipour, 2014)

Kepler 38 - Evolution of surface density



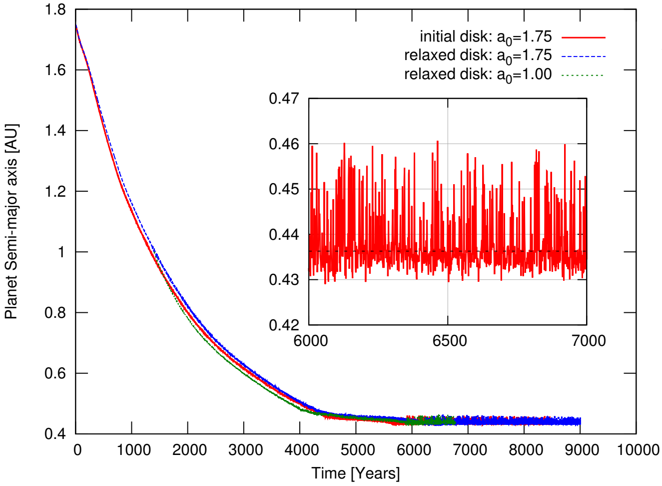
Initial profile:
$\Sigma \propto r^{-1/2}$

Equilibrium:
after $\approx$ 3000 yrs

Outer Boundary:
Σ fixed

Inner Boundary:
Open

Kepler 38: Migration of planet in disk



Add Planet with:
$m_p = 0.36 M_{\text{Jup}}$

Planet stops at gap edge with:
$a_p = 0.43$ AU
$e_p = 0.15$

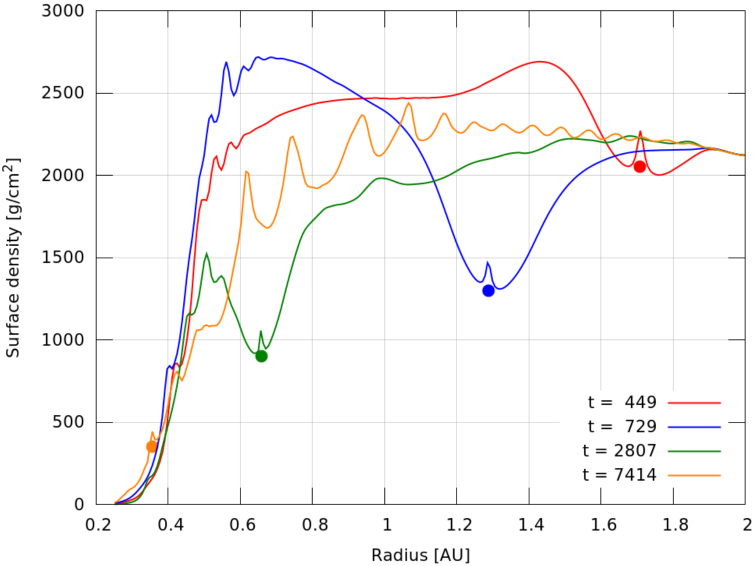
Observed Planet Parameter:
$a_p = 0.46$ AU
$e_p = 0.03$

Planets started at different distances, in original/relaxed disks

All stop at same distance: at ≈ 0.43 AU

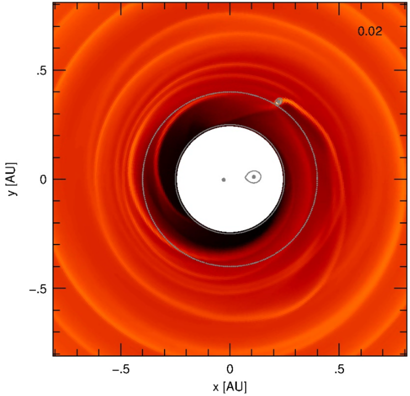
Surface density with planet

Planet is 'parked' at inner edge of disk



Animation: Planet in disk

Animation of Disk and Planet around Binary Star
(shown is the final phase, in 5:1 resonance)



- 5:1 probable unstable upon disk dissipation
- some planet evolutions are unstable
- inside observed location and too high eccentricity
- vary disk properties to achieve stopping further out
- and use radiative disks

Summary/Outlook

Results: Kepler 38:

- Circumbinary planets can be explained by a migration process
- Planets are 'parked' near gap edge, just outside of instability region
- Exact location depends on disk physical parameter

Open issues:

- Disk structure not clear - even without planet
- Todo: Parameter variation, radiative disks, 3D simulations

Eccentric binary, System Parameter

Comparison: Kepler 38 and Kepler 34

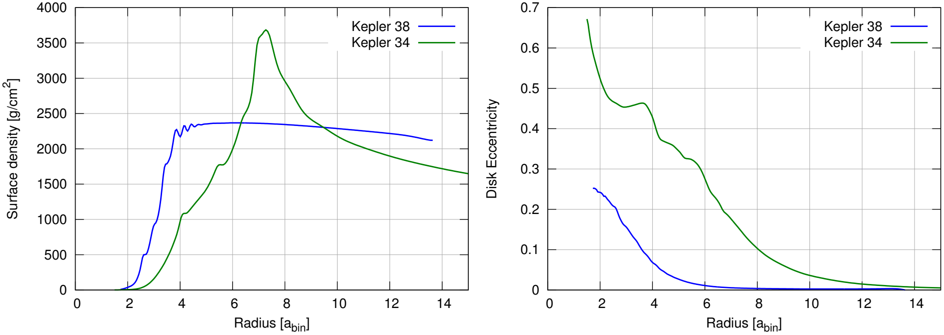
Binary Parameter:

	(Kepler 38)	(Kepler 34)
$M_1\,[M_\odot]$	0.95	1.05
$M_2\,[M_\odot]$	0.25	1.02
P_B [days]	18.6	28
a_B [AU]	0.15	0.23
e_B	0.10	0.52

Planet Parameter:

	(Kepler 38)	(Kepler 34)
$m_p[M_{\mathrm{Jup}}]$	0.36	0.21
P_p [days]	105.6	288
a_p [AU]	0.46	1.09
e_p	0.03	0.18

Surface density and eccentrictiy of disk with no planet

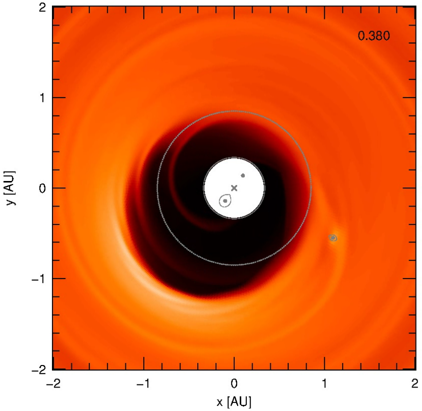


Differences to low eccentric binary:

- larger inner hole
- spike in density
- high disk eccentricity

Animation: Planet in disk

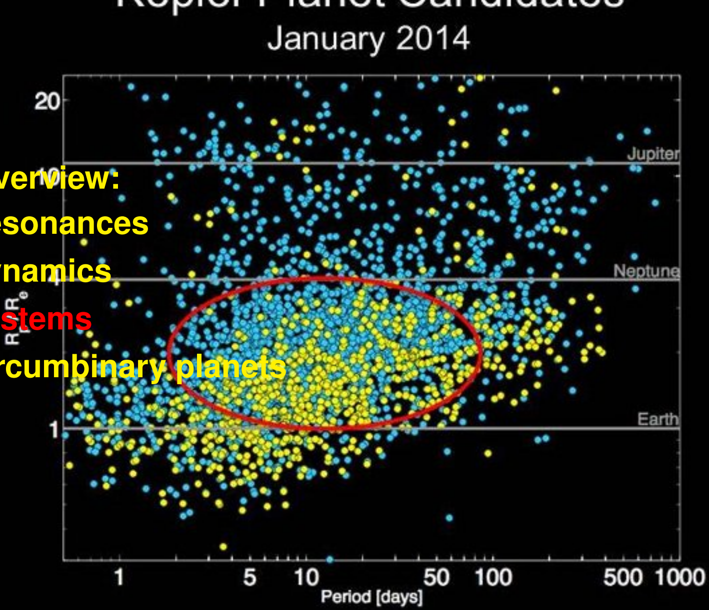
Animation of Disk and Planet around Kepler 34
(shown is the final phase)



Summary: eccentric binary

- Large (eccentric) hole in center of disk
- Planet stops too far out
- Vary disk parameter ?
- Multiple planets ?

Organisation



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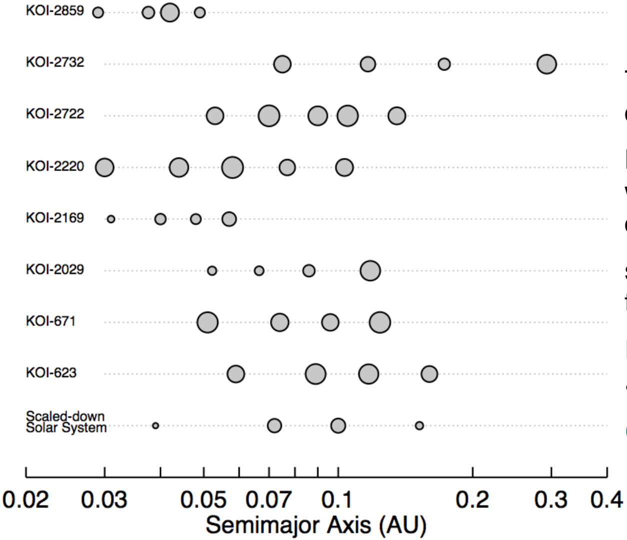
Systems of super-earths: Examples

Super-earth systems with $R_p < 1.5 R_{earth}$ in comparison to the Solar System



Top: 8 Kepler candidate systems

Bottom: Solar System, with distance scaled down by factor 10

size scaled to radius of the planet

For reference:
$a_{Earth}/a_{Venus} = 1.6$

(Raymond, ea. 2014)

Systems of super-earths: Characteristic

Some characteristics of Hot-super Earth systems

- terrestrial-like exoplanets
  radii between Earth and Neptune
  often in multiple systems
- extremely common
  30-50% of Sun-line stars (FGK) host at least one planet with mass less than $10 M_{earth}$ with period less than 50-100 d.
  Probability around M-stars at least as high
- orbits
  typically compact systems on non-resonant orbits
  orbital separations comparable to Solar System planets, in terms of Hill-radii

Systems of super-earths: Formation

Some suggested formation scenarios

1) in situ formation in massive disk
2) accretion during inward type I migration
3) sheparding by interior mean-motion resonances of inwardly migrating massive planets
4) sheparding by interior secular resonance inwardly migrating massive planets
5) circularisation of high-eccentric planets by tidal interactions with star
6) photo-evaporation of close-in giant planets

Numbers 3) to 6) can be ruled out theoretically and observationally (Raymond ea. 2014)

Systems of super-earths

Conflicts:

3)-4) require giant planet to drive planets inward and an additional disk to damp eccentricity in both scenarios a giant planet should be present just outside of outmost planet which is not obeserved

5) circularization in principle possible (see above) but require large initial eccentricities that would result in single-planet systems, which is in conflict with observations

6) evaporation is possible for very close in planets, requires Gyr to operate. Strongly depends on distance from central star. Would only allow the innermost planet to be evaporated.

Hence 1) (in situ) and 2) (inward type I migration) are the leading contestors

(Haghighiour 2013; Raymond ea. 2014)

Comments on scenarios

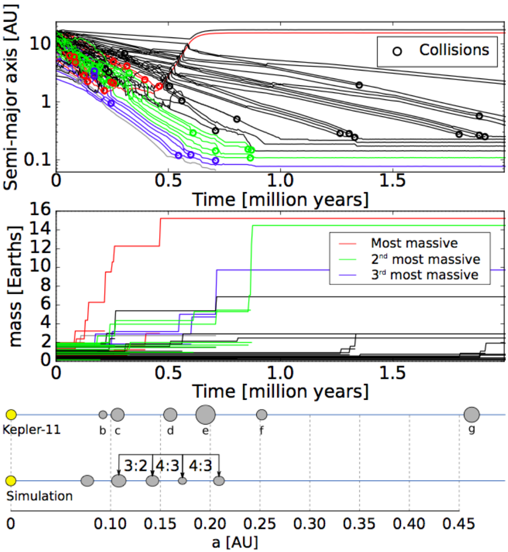
1) in situ
Requires migh mass ($\approx 20 - 40 M_\oplus$) within fraction of an AU
within a MMSN context: $\Sigma = \Sigma_0 (r/AU)^{-x}$, need steep powerlaw
$x = 1.6 - 1.7$ and 10 times higher normalisation Σ_0.
i.e. high total disk mass
Observations indicate shallower profile: $x \approx 0.5 - 1.0$

But: Simulations show that orbital properties (eccentricities, inclinations, separations) match observations

2) migration
Simulations of migration super-earths show the formation of resonant chains
destabilisation $\Rightarrow$ collisions and accretion
consecutive chain formation (see example below)

Possible distinction betwen models:
1) naked high-density rocks 2) lower density material containing ice
but possible atmosphere could hide effect

Example formation scenario



Formation of hot super-Earths by type I migration
Top: orbital distances
Middle: mass growth
Bottom: Comparision

size scaled to radius of the planet

For reference:
$a_{Earth}/a_{Venus} = 1.6$

(Cossou ea. 2014)

Further Reading

- Resonances:
  Murray & Dermott (1999), Kley et al. (2004)
- Multiple:
  Fabrycky & Tremaine (2007)
- Super-Earths:
  Haghighipour (2013), Raymond et al. (2014)